CIV5000Z: DISSERTATION FOR THE DEGREE OF MASTER OF SCIENCE

Simplification of Complex WWTP Models into Simple Design and Evaluative WRRF Tool

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Dissertation/Thesis/Project submitted in fulfilment of the requirements for the degree of "Degree"

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Declaration

I, Olivier Nsengiyumva, know the meaning of plagiarism and declare that all the work in this document, save for that which is properly acknowledged, is my own.

Signed: Signed by candidate Date: 20-10-2020

Acknowledgements

I would like to take this opportunity to acknowledge my gratefulness to a number of individuals who contribute directly or indirectly to the completion of this research project:

- First and fore foremost, I would like to thank God Almighty for giving me strength and comfort throughout the duration of this project.
- I would like to thank my supervisor and co-supervisor Dr David Ikumi and Prof George Ekama, for sharing their knowledge and motivating me to complete this project.
- I would like to thank those who funded my studies among who are the University of Cape Town (UCT), the Civil Engineering research group at UCT, Water and Research Commission and John Davidson educational trust.
- I would acknowledge Prof Chris Brouckaert and Dr Barbara Brouckaert for helping in the first stages of the tool development. Thank you for the collaboration and for developing the fractionator which was used in this project.
- I would like to acknowledge Mr Olando and Mr Seabelo for conducting surveys with different stakeholders. Their contribution enabled me to collaborate with these stakeholders in the tool development.
- Mr Kirshen Naidoo and the Water and Research Commission team, thank you for the collaboration on this project and for giving me the exposure of presenting the developed tool at the IMESA conference.
- Lastly, I would like to thank my family, friends and colleagues who supported in different ways. Your support is much appreciated.

Abstract

Wastewater treatment plant (WWTP) steady-state models have been used, historically, by consulting engineers and researchers for design, process optimisation, and to study and evaluate various operating scenarios. These models have, however, been generally developed for single unit process which limits their use. In addition, there have been three recent shifts in the past two decades from conventional design and modelling of WWTPs. Firstly, the shift from single unit to plant-wide modelling. Secondly, WWTPs are considered as water and resource recovery facilities (WRRFs). Lastly, there has been a growing interest to use the developed plant-wide steady-state models by stakeholders i.e., plant operators, designers and decision-makers who have limited technical expertise in WWTP modelling. These stakeholders use these models for design, evaluation and optimisation of scenarios. The later shift has raised the debate of complexity versus simplicity of the developed steady-state models. In addition to the aforementioned shifts, there has been limited research on the impact of sludge return liquors on the overall plant performance especially in the context of South African WWTPs. Wastewater treatment plants treat influent wastewater to a specified effluent quality, through several processes, before discharging it into the receiving water bodies. One of the by-products of these treatment processes is a nitrogen (N) and phosphorus (P) rich dewatering liquor (DWL). Generally, South African WWTPs recycle the DWL to the mainstream treatment process without first undergoing any side-stream treatment process (SSTP). The recycling of such N and P rich DWLs to the mainstream process, without first going through any SSTP and/or addition of organics to the mainstream process (organics have a role to play in nutrient removal, through the provision of substrate for biomass growth and provision of electron donors in the process of denitrification) poses a problem to the treatment process. Consequently, the reactor is overloaded with nutrients without sufficient organics to remove them; hence, the plant produces poor effluent quality i.e., high N and P concentrations at high operational cost. A simplified full-scale steady-state WWTP simulation tool, namely, plant performance evaluation tool (PPET), with a user-friendly interface was developed, based on principles of sound mass balance and kinetic and stoichiometric relations over the full-scale plant, to bridge the gap between the complexity of WWTP models and the lack of technical expertise of the stakeholders. This simulation tool analyses the impact of recycling sludge dewatering liquors on the overall plant performance. Furthermore, it gives the user a platform to analyse different scenarios and provides

uncompromised results that enable the user to make better design and operation decisions. The bio-augmentation batch enhanced (BABE) and struvite precipitation SSTPs, and plant performance indices i.e., effluent quality and operational cost indices, EQI and OCI, respectively, were incorporated into PPET to analyse case studies on South African plants. It was found that there are added benefits of using a SSTPs to mitigate the detrimental impacts of recycled DWL when the capacity of the plant has been exceeded. However, both BABE and struvite precipitation processes achieve different results based on the composition of the DWL that is being treated i.e., for DWL from an anaerobic digester treating waste activated sludge that is not P rich (with low EBPR), then the recommended SSTP operation would be BABE process rather than struvite precipitation. Due to the different treatment systems (i.e., with variations in influent loads, system configurations and priority end products required - energy, water, phosphorus, etc.), further investigations are required on strategies for implementation of the various SSTPs.

Table of contents

List of Tables

List of Figures

List of Symbols and Abbreviations

%	Percentage
°C	Celsius
a	Recycle ratio from aerobic to anoxic reactor
AD	Anaerobic Digester
ADWF	Average Daily Weather Flow
AE	aeration energy (kWh/d)
ANNAMOX	Anaerobic Ammonium Oxidation
ANOs	Autotrophic/Ammonia Nitrifying Organisms
AS	Activated Sludge
ASM	Activated Sludge Model
BABE	Bio Augmentation Batch Enhanced
b_H	Endogenous Respiration Rate (/d)
BNR	Biological Nutrient Removal
BOD_5	Biochemical Oxygen Demand
BPO	Biodegradable Particulate Organics
BSM	Benchmark Simulation Model
BSO	Biodegradable Soluble Organics
C	Carbon
$CaCO_3$	Calcium Carbonate
CH_4	Methane Gas
CHPs	Combined Heat and Power Systems
C_N	Concentration of the Substrate, NH4-N (g/m3)
CO_2	Carbon Dioxide

COD	Chemical Oxygen Demand
CPU	Central Processing Unit
C_{st}	Not electron acceptor depending
d	Day
Den PAO	Denitrifying PAO activity included
dN_a	Ammonia utilisation rate (mgN/l)
dN_n	Nitrate Utilisation Rate (mgNO3-N/l)
DR	Death Regeneration Concept
DWA	Department of Water Affairs
DWS	Department of Water and Sanitation
DWL	Dewatering Liquor
EA	Electron Acceptor Depending
EBPR	Enhanced Biological Phosphorus Removal
EC	External Carbon Addition (kgCOD/d)
EQI	Effluent Quality Index
ER	Endogenous Respiration Concept
f	Unbiodegradable Fraction of OHOs
f_c	Carbon to COD Ratio
f_{cv}	COD/VSS ratio of the organics (mgCOD/mgVSS)
F-RBCOD	Fermentable Readily Biodegradable COD
FSA	Free and Saline Ammonia
g	Gram
H	Hydrogen
H+	Hydrogen Ion

H^+	Hydrogen Ion
H_2	Hydrogen Molecule
H_2O	Water
HAc	Acetic Acid
HCO_3^-	Bicarbonate
HE	Total Heat Energy Required in the Anaerobic Digester for Sludge Treatment (kWh/D)
HPr	Propionic Acid
ISS	Inorganic Suspended Solids
IWA	International Water Association
JHB	Johannesburg
K_1	Initial Rapid Specific Rate of Denitrification in Primary Anoxic Reactor (mgNO3-N/mgOHOVSS.d)
K_2	Second Specific Rate of Denitrification in Primary Anoxic Reactor (mgNO3-N/mgOHOVSS.d)
K_3	Specific rate of denitrification in secondary anoxic reactor (mgNO3-N/mgOHOVSS.d)
K_4	Specific Rate of Denitrification in Anoxic-Aerobic Digester (mgNO3-N/mgOHOVSS.d)
k_{add}	Specific Addition Rate of Nitrifiers(/day)
k_D	Endogenous Decay Coefficient of Autotrophs (/day)
K_N	K_N = Half-Rate Constant For Nitrifiers (g/m^3)
K_{nT}	Half Saturation Constant
K_S	Substrate Half Maximum Saturation Coefficient (mgCOD/l.)
kWh	Kilo-Watts Hour

l	Litre
m	Metre
m^3	Cubic Metre
ME	Mixing Energy (kWh/d)
Mg	Magnesium
mg	Milligram
$MgNH_4PO_4.6H_2O$	Struvite
Ml	Megalitre
MLE	Modified Ludzack-Ettinger
MP	Energy from Methane Produced (kWh/d)
N	Nitrogen
N_a	Ammonia Concentration (mgN/l)
ND	Nitrification-Denitrification
NDEBPR	Nitrification-Denitrification Enhanced Biological Phosphorus Removal
NH_3	Ammonia
NH_4^+	Ammonium
N_n	Nitrate Concentration ($mgNO_3$-N/l)
NNOs	Nitrite-Oxidizing Organisms
NO	Nitrate
NO_2^-	Nitrite
NO_3^-	Nitrate
O	Oxygen
O_2	Oxygen Molecule
O_c	Carbonaceous Oxygen Utilisation Rate (mgO_2/l.d)

OCI	Operational Cost Index
OHOs	Ordinary Heterotrophic Organisms
On	Nitrification Oxygen Utilisation Rate (mgO2/l.d).
OP/OrthoP	Orthophosphate
P	Phosphorus
PAOs	Polyphosphate Accumulating Organisms
pCO_2	Partial Pressure of Carbon Dioxide
PE	Pumping Energy (kWh/d)
pH_2	Hydrogen Partial Pressure
PHA	Poly- β-hydroxyalkanoates
PO_4	Phosphate
PP	Polyphosphate
PPET	Plant Performance Evaluation Tool
PS	Primary Sludge
PST	Primary Settling tank
PWM_SA	Plant-Wide Model of South Africa
PWWF	Peak Wet Weather Flow
Q_w	Waste Flow
r	Recycle Ratio from Anoxic Reactor to Anaerobic Reactor
RBCOD	Readily Biodegradable COD
Rs	Sludge Age (d)
S	Recycle Ratio from Secondary Settling Tank to Anoxic Reactor
S_b	Concentration of Biodegradable Organic Material (mgCOD/l)
SBCOD	Slowly Biodegradable COD

SP	Sludge Produced (kgTSS/d)
SRC	Standardised Regression Coefficients
SRT	Solid Retention Time (d)
SRT^{min}	Minimum Sludge Retention Time (d)
SSTP	Side-Stream Treatment Process
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
TSS	Total Suspended Solids
UCT	University of Cape Town
UPO	Unbiodegradable Particulate Organics
USO	Unbiodegradable Soluble Organics
VBA	Visual Basic for Applications
VFA	Volatile Fatty Acids
VSS	Volatile Suspended Solids
WAS	Waste Activated Sludge
WRC	Water and Research Commission
WRRF	Water and Resource Recovery Facility
WWTmod2016	Wastewater Treatment 2016 Modelling Conference
WWTP	Wastewater Treatment Plant
XBA	Autotrophic Nitrifying Organism Concentration (mgANOVSS/l)
X_E	Endogenous Residue Concentration (mgVSS/l)
Y_A	Yield Coefficient of Nitrifiers (mgVSS/mgN)
Y_H	Yield Coefficient of Ordinary Heterotrophic Organisms

μ	Specific Growth Rate of Organisms (g/g.d)
μ_{aMt} or μ_m	Maximum Specific Growth Rate (mgANOVSS/mgANOVSSS/d)
μ^{max}	Maximum Specific Growth Rate of Nitrifiers (/day)

1. Introduction

1.1 Background to the Project

Historically, wastewater treatment plant (WWTP) models have been used by consulting engineers and researchers for design, process optimisation and to study interactions between various biological and chemical processes taking place in these plants (Lizarralde *et al*., 2018). However, in the past 20 years, there have been two major shifts in the design and operation of WWTPs : (i) the paradigm shift involving the conversion of WWTPs to water and resource (including water, minerals and energy) recovery facilities (WRRFs) (Mo and Zhang, 2013; Ekama, 2017) and (ii) increased interest in the utilisation of WRRFs models by various stakeholders (i.e., plant operators, designers and decision-makers), including those with limited technical expertise in the WRRF modelling. The utilisation of WRRF models could vary from their application as tools for education on the relevant system processes and parameters to their provision of expert-guidance during decision-making in design and/or process optimisation (Menniti *et al*., 2018). Although several plant-wide steady-state tools such as the work of Wu and Ekama (2015) have been developed, the challenge with these simulation tools is that they are too complex and unrelatable to be used by the stakeholders, hence, there is a necessity to simplify these tools to increase their uptake by stakeholders. Lizarralde *et al*. (2018) summarises the challenges that have to be overcome in simplifying these tools: (i) the limited knowledge of the new stakeholders; (ii) the usefulness and trustworthiness of the information generated by these tools (i.e., the applicability of these tools); and (iii) simplifying the complex models without compromising their outputs. Menniti *et al*. (2018) recommend that, to overcome such challenges, the modeller should work closely with the involved stakeholders and that the accuracy of the model outcome should be made clear in the developmental stages of the model. Furthermore, stakeholders should be trained on how to use the models where necessary. Simplified tools will be useful to decision-makers and plant designers in their evaluation of strategies in WRRF design and optimization to ensure better-informed decision making.

With the conversion of WWTPs to WRRFs, various technologies for recovery of nutrients (e.g., struvite crystallisation units) have been developed that could be implemented as side-stream unit processes of WRRFs. The strategy of implementing of such side-stream unit processes in the WRRF instrumentation could be evaluated against the recycling of nutrient-rich (with high concentrations of nitrogen (N) and phosphorus (P)) sludge dewatering liquors (DWLs). The impact of recycling such a highly concentrated N and P DWL to the mainstream process, may include overloading of the plant with nutrients, which usually require the addition biodegradable organics for their removal in the activated sludge reactors (organics have a role to play in nutrient removal, through the provision of substrate for biomass growth and provision of electron donors in the process of denitrification). Consequently, the result is often poor effluent quality and high operational costs (Vogts *et al*., 2015 and Ekama, 2017). South African WWTPs, generally, recycle DWL to the mainstream treatment processes without undergoing further side-stream treatment; therefore, evaluating the impact of recycling DWL to the biological nutrient reactor (BNR) activated sludge (AS) reactor, and the benefits of having a side-stream treatment process (SSTP) are of great importance.

1.2 Scope of the Project

The scope of this project is limited to simplifying the current complex steady-state plant-wide models into evaluation tools that can be used by the newly interested stakeholders i.e., plant operators and supervisors who do not necessarily have the technical expertise on the complex processes that happen in the plant. The simplification process entailed incorporating an influent wastewater fractionation model in the complex steady-state plant-wide WRRFs models and then developing a user-friendly interface. Furthermore, plant performance indices, used by the international Water Association (IWA) Benchmark Simulation Model (BSM) task group namely, effluent quality and operational cost index (EQI and OCI, respectively; Jeppsson et al., 2007) will be incorporated in the plant performance evaluation tool (PPET) with the intent of evaluating the impact of recycled liquors on the overall plant performance. These performance indices have been fine-tuned for South African WWTP conditions (de Ketele et al., 2018).

1.3 Key Questions

The following key questions were posed with the aim of conducting this research:

- Is it possible to convert complex WWTP models to simple WRRF tools that can be used by plant operators and designers?

- Is there any added value to having a side-stream treatment process (SSTP) to the overall plant performance, evaluated based on the effluent quality and operational cost indices?
- What impact does the recycling of sludge dewatering liquors have on the overall plant performance of the wastewater treatment plant?

1.4 Hypothesis

Based on the reviewed literature and the posed key questions, the following hypothesis will be tested:

Through the knowledge of the influent wastewater characteristics and plant-wide mass balance principles, the fate of organics can be traced throughout the plant. It is, therefore, possible to simplify complex WWTP models to user-friendly WRRF tools that can be used by different stakeholders without compromising the outputs from these tools. Lastly, there is an added benefit of incorporating a SSTP in the plant layout i.e., better effluent quality and lower plant operating costs.

1.5 Objectives

The overreaching objective of this research project is to develop a simplified and user-friendly plant-wide steady-state tool (hereafter referred to as the plant performance evaluation tool, PPET) that can be used by different stakeholders to evaluate the impact of recycling sludge dewatering liquors on the overall plant performance for South African WWTPs. Additionally, this tool would provide a recommendation to the best SSTP to incorporate in the plant layout.

1.5.1 Conversion of Complex WWTP Steady-State Mathematical Models into a Simple WRRF Design Evaluation Tool

The main goal of this sub-objective is to develop an integrated, mass balanced, plant-wide WWTP steady state model (through linking unit process model equations for primary settling, activated sludge and anaerobic digestion) and simplify it into an evaluation tool to encourage uptake by decision-makers. Simplifying this integrated plant-wide steady-state model allows potential users to selectively engage with the model, according to the variables and parameters that are deemed to be of importance for the performance of their systems. This simplification involves the provision of a user-friendly interface. An important addition to this tool (i.e., the simplified steady-state model) is the evaluative function that entails contrasting the benefits for having a SSTP against recycling the DWL; IWA BSM task group evaluation indices namely EQI and OCI are used here.

1.5.2 Comparing Simplified Steady-State Tool with Validated Steady-State Model

Once the simplified steady-state model has been developed, its outputs (results) will be compared with a validated plant-wide steady-state model of Ekama (2009), run under the same steady-state conditions. The main aim of this comparison is to assess whether there are any discrepancies between both results and hence build confidence in the developed tool.

1.5.3 Incorporating SSTPs in PPET

The incorporation of SSTPs into the developed tool is one of the main objectives of this research. The aim of incorporating SSTPs in the developed tool was to evaluate the impact of recycling sludge DWLs on the overall plant performance. The main SSTPs that were incorporated in the tool are bio-augmentation batch enhanced (BABE) and struvite precipitation processes. These processes were selected because they are best suited for South African WWTP operational conditions.

1.5.4 Case Studies on South African WWTPs

Lastly, the simplified plant-wide steady-state tool would be used in case studies on South African plants to illustrate the capabilities or potential of applying the modelling tools.

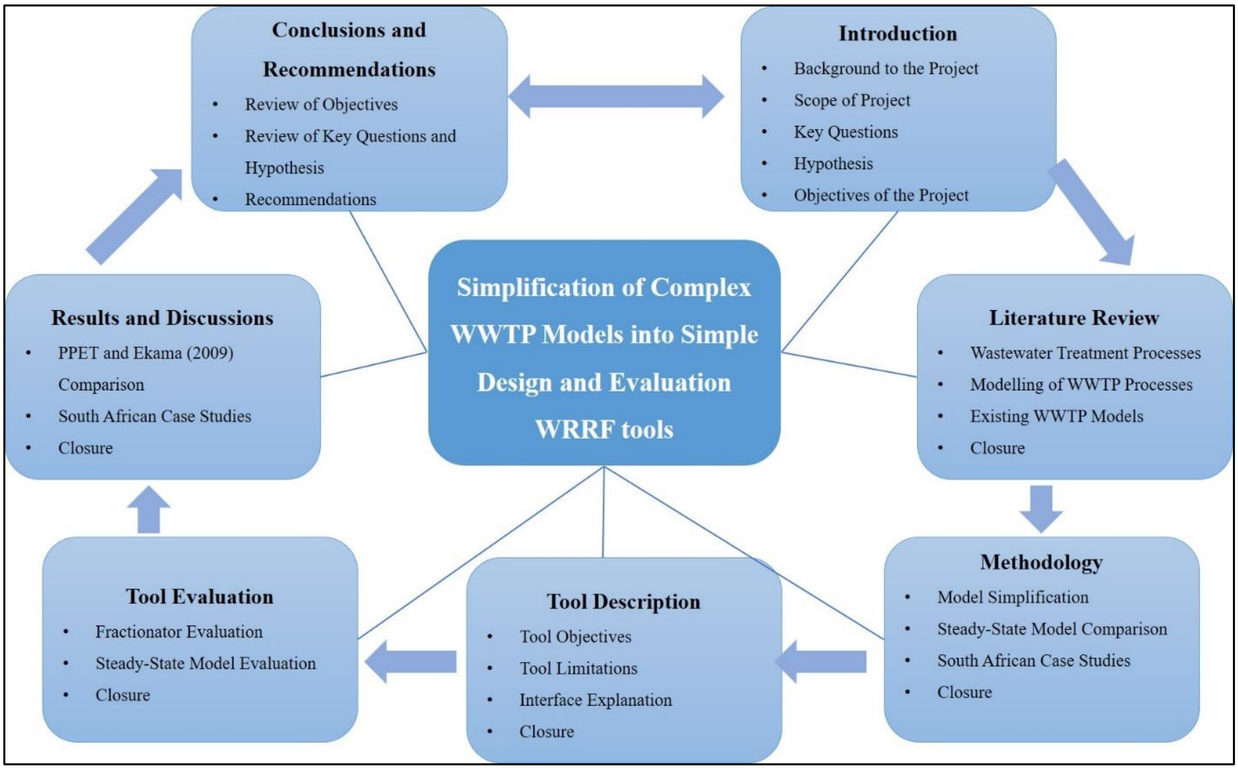

Figure 1-1: Overview of the Project Report

The development of the tool involved the following processes as described in the subsequent chapters: (i) perform a literature review study on feasible SSTP for South African WWTPs that would mitigate the detrimental effects of untreated recycled DWL; (ii) develop a simple model toolbox that will enable decision-makers and designers to evaluate the impact of sludge return liquors on performance of the AS system; and (iii) perform an experimental case study on the impact of recycling dewatering liquors to the influent of selected South African full-scale WWTPs.

2. Literature Review

This literature review comprises of three sections. Section 2.1 briefly discusses the overview of a wastewater treatment plant (WWTP) processes i.e., its objectives and the different processes under which wastewater goes through before it is discharged into the receiving water body. Furthermore, the transition from WWTP to water and resource recovery facilities (WRRFs); and the plant performance criteria are also briefly discussed. The aim of this overview is to establish a background knowledge that is needed in the understanding of the system modelling process. The term WWTP and WRRF have been used interchangeably throughout this literature review. Section 2.2 discusses the state of the art for mathematical models (i.e., steady-state and dynamic) that replicate wastewater treatment processes and the role of these models in evaluating WWTP design and process optimization. Furthermore, this section discusses different modelling methodologies that have been used in developing WRRF simulation models. Section 2.3 looks briefly at the application of the developed simulation models and the recent interest in using these sets of engineering tools by various stakeholders (i.e., with different levels of technical knowledge). This section includes a discussion of the key elements that must be considered while simplifying “complex” WWTP mathematical models to easy-to-use tools.

2.1 Wastewater Treatment Processes

2.1.1 Brief Overview

Historically, wastewater treatment plants (WWTPs) have been designed to remove pollutants from municipal or industrial wastewater, through a series of physical, chemical and biological processes before releasing it into the receiving water bodies (Hreiz, *et al*., 2015). Water, as a naturally occurring resource, has several uses such as domestic use, industrial processes, agriculture and recreational activities. However, it is not always readily available in the most suitable state for use and many regions remain water-scarce or have their water sources subject to adverse effects of pollution. The treatment of wastewater is vital for protecting water bodies from harmful chemical substances that are present in the sewage and for water reclamation so that it can be reused in different forms depending on its quality. Table 2-1 summarises some of the effluent quality limits as recommended by the South African Department of Water Affairs (DWA), now called the Department of Water and Sanitation (DWS).

Table 2-1: General and special wastewater effluent quality limits applicable for discharge into a water body (Department of Water Affairs, 1999)

Parameter	General Limit	Special Limit
COD (mg/l)	75	30
Nitrate as N (mg/l)	15	1.5
Ammonia as N (mg/l)	6	2
Orthophosphate as P (mg/l)	10	1 (median) & 2.5 (maximum)

The chemical oxygen demand (COD), nitrogen and phosphorus limits are specified in Table 2-1 because they are the most challenging to achieve and treatment plants are designed primarily to remove them. Ekama and Wentzel (2008a) summarize the primary objectives of wastewater systems as:

- To remove biodegradable organics so that there will not be deoxygenation in the receiving waters due to heterotrophic growth,
- To remove or reduce nitrogen (N) and phosphorus (P) nutrient concentrations from sewage to prevent eutrophication in the receiving waters, and
- To remove ammonia which is toxic and prevent further deoxygenation in the water body.

Recently, there has been a paradigm shift in the design and operation of wastewater treatment plants (WWTPs) as water and resource recovery facilities (WRRFs) (Ekama, 2017). This shift was inspired by the awareness that WWTPs consume a large number of resources and energy (up to 23 % of municipal energy is consumed) (Mo and Zhang, 2013). Hence, for sustainable design and environmental preservation, WWTPs should be designed such that they mitigate loss in scarce resources, reduce waste generation and maximize their potential for resource (mainly water, energy and nutrients) recovery (Lundin, *et al*., 2000). Mo and Zhang (2013) discuss three main sources of resources recovery in treatment plants. These include (i) onsite energy recovery in the form of biogas through combined heat and power systems (CHPs) can generate 350kWh per million gallons of wastewater, (ii) biosolids combustion and hydropower generation from the effluent water, (ii) nutrient (N and P) and biosolids recovery for use as fertiliser, soil conditioner or as raw material to other processes, (iii) recycling wastewater as an alternative source of water supply either for portable purposes or other activities such as agriculture, landscape irrigation and flushing toilet (Adewumi, *et al*., 2010, Mo and Zhang, 2013). This paradigm shift or resource recovery facilities affects the conventional design and operation of treatment plants. Consequently, adding another dimension to the current models that are in use.

2.1.2 WWTP Processes

The influent raw wastewater goes through several processes, namely but not limited to, primary and secondary sedimentation, biological nutrient removal, sludge and dewatering liquor treatment, so that the specified effluent quality standard may be achieved. The sophistication of these processes depends on the influent wastewater composition and the effluent quality requirements. The main treatment processes that are relevant to this research have been briefly discussed in the following subsections.

2.1.2.1 Sedimentation

The main objectives of the sedimentation process are to separate the liquids and solids waste constituents of the influent wastewater, in the primary settling tank (PST); and to thicken and store sludge, in the secondary settling tank (SST).

Primary Settling Tank

The PST unit plays a role of splitting the influent wastewater where the settleable particles are separated from soluble and non-settleable solids. This process achieves about 30 to 50% of the influent organic nutrient (COD) removal (Ekama and Wentzel, 2008a). Consequently, the PST contributes to a reduction in reactor volume, lower oxygen demand and lower secondary sludge production.

Secondary Settling Tank

The SST unit plays a crucial role in the solid-liquid separation of the mixed liquor from the bioreactor. The performance of the SST affects the success of the activated sludge system, thus the overall plant performance (De Clercq, *et al*., 2008; Jin, *et al*., 2003). The objectives of the secondary settling tank unit can be subdivided into three, namely, (1) effluent clarification so that the suspended solids concentration in the effluent is not exceeded; (2)sludge thickening before recycling it to the biological reactor; and (3) sludge storage when necessary (Bürger, *et al*., 2011).

2.1.2.2 Biological Nutrient Removal

Biological nutrient removal (BNR) activated sludge systems operate primarily to remove the most harmful pollutants, i.e., biodegradable organics, and nitrogen and phosphorus nutrients (Ekama and Wentzel, 2008a) through various biological processes; mediated by various types of microorganisms that reside in the reactors for a given solids retention time. Organic removal is facilitated by ordinary heterotrophic organisms (OHOs) (Ekama and Wentzel, 2008a). These organisms utilise influent biodegradable organics (i.e. soluble and particulate) for biomass growth. The generated biomass becomes part of the volatile suspended solids (VSS) in the biological reactor. Active biomass undergoes further process of endogenous respiration (Section 2.3.3.1) to produce unbiodegradable particulate fraction. The influent inorganic suspended solids (ISS) are enmeshed with influent unbiodegradable particulates are wasted through the daily reactor waste flow. Nitrogen removal occurs through nitrification and denitrification processes. Nitrification is a process through which free and saline ammonia (FSA) is converted into nitrate by autotrophic nitrifying organisms (ANOs) whereas denitrification is a process through which the generated nitrate is oxidized (by heterotrophic organisms) to nitrogen gas in the unaerated zone (Ekama and Wentzel, 2008b). The BNR systems that incorporate the nitrification process result in longer sludge ages because the specific growth rate of ANOs is slower compared to that of other micro-organisms in the wastewater. The phosphorus (P) constituents are removed by polyphosphate accumulating organisms (PAOs) (Wentzel *et al*., 1990; van Loosdrecht *et al*., 2008) that can accumulate large quantities of P aerobically. Their complex metabolic behaviour is described in Section 2.3.3.4.

There are several BNR configurations that were developed over time for the treatment of wastewater. The choice of the BNR configuration to use depends on the type of wastewater pollutant to be removed and the influent wastewater characteristics. For the choice of the BNR configuration based on the type of pollutant to remove, systems such as nitrification-denitrification (ND) configurations (e.g. Modified Ludzack-Ettinger (MLE)); enhanced biological phosphorus removal (EBPR) configurations (e.g. Phoredox system); and nitrification-denitrification enhanced biological phosphorus removal (NDEBPR) configurations (e.g. the University of Cape Town (UCT) and Johannesburg (JHB) layouts), can be used to remove nitrogen, phosphorus, or nitrogen and phosphorus nutrients, respectively. On the other hand, for the choice BNR configuration based on the influent wastewater characteristics, for the Phoredox process, where complete denitrification is a requirement, a TKN/COD ratio between 0.07 to 0.08 mgN/ mgCOD is feasible whereas, for the UCT system where complete denitrification is not a requirement for excess P removal, TKN/COD of more than 0.08 mgN/ mgCOD is feasible (Ekama *et al*., 1983). Both the influent wastewater characteristics and the type of wastewater pollutant to remove are used as guides to the selection of the most suitable BNR configuration. For the sake of this literature review, the four most commonly used biological reactor configurations in South Africa viz. MLE, 3-Stage Phoredox, UCT and JHB configurations (Wu & Ekama, 2015) will be discussed. Van Loosdrecht *et al*. (2008) discuss several other configurations.

MLE System

The Modified Ludzack-Ettinger, MLE, (Figure 2-1) was proposed by Barnard in 1973 with the aim of removing nitrogen from the wastewater through a nitrification-denitrification process. It consists of a complete separation of the primary anoxic reactor, where denitrification takes place and the aerobic reactor where nitrification takes place.

In this configuration, mixed liquor is recycled from the aerobic to the anoxic zone and sludge is recycled from the secondary settling tank to the anoxic reactor. The sludge age and the fraction of the unaerated mass fraction in the anoxic reactor are the most important limiting factors for nitrification (Ekama and Wentzel, 2008b). This system achieves approximately 85% of nitrogen removal and is well suited for influent TKN/COD ratio above 0.10 mgN/mgCOD (Wu and Ekama, 2015). Ekama and Wentzel (2008b) recommend that a high underflow rate (i.e., a ratio of 1:1 to the influent flow rate) should be used to avoid the possibility of rising sludge in the secondary settling tank due to denitrification.

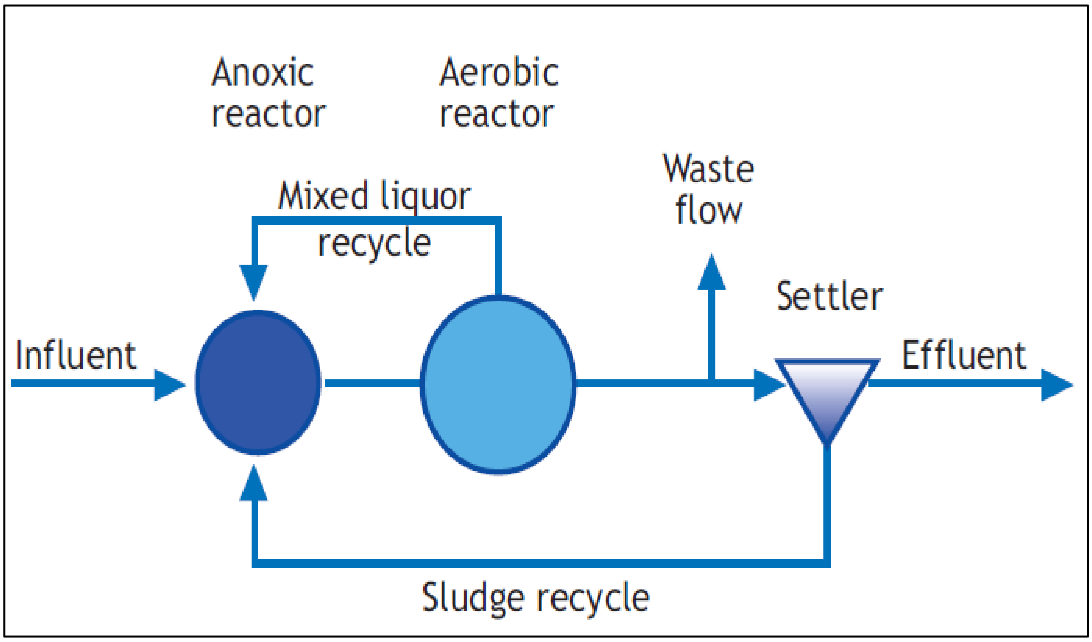

Figure 2-1: Modified Ludzack-Ettinger system (Ekama and Wentzel, 2008b)

3-Stage Phoredox System

The 3-Stage Phoredox system (Figure 2-2) is designed around the removal of phosphorus. The mixed liquor is recycled from the aerobic zone to the anoxic zone to ensure that there will be minimal or no nitrates and oxygen in the return sludge since their presence would affect the phosphorus release in the anaerobic zone.

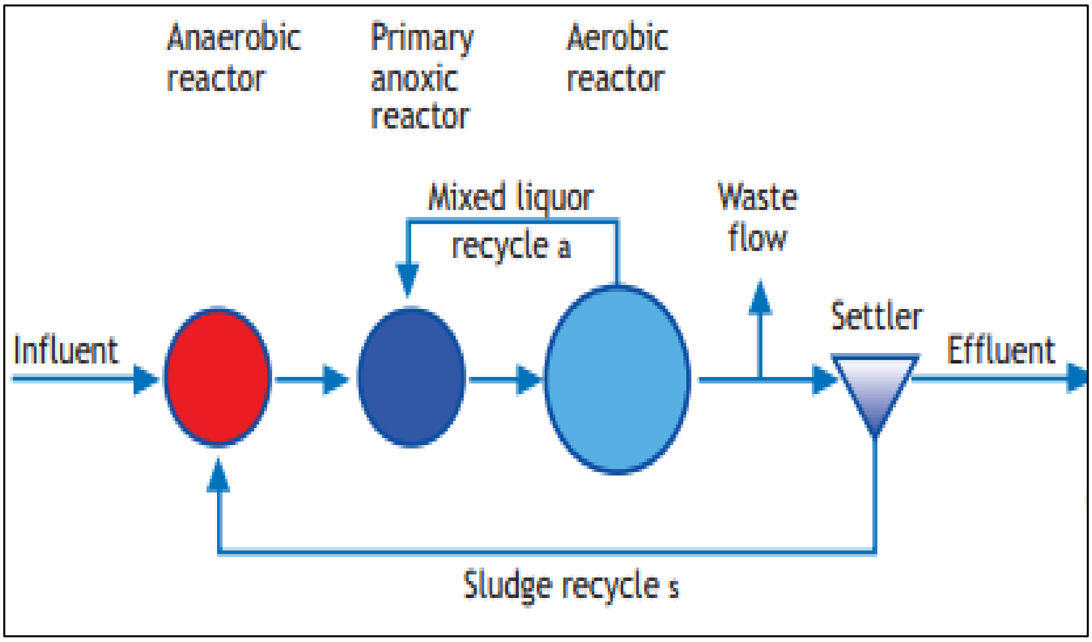

Figure 2-2: 3-Stage Phoredox (van Loosdrecht *et al*., 2008)

In the case where there is a high concentration of nitrates in the return sludge, the 3-stage Phoredox can be modified into a JHB system by adding another anoxic zone to remove the nitrates from the sludge before recycling it to the anaerobic zone (Stratful, *et al*., 1999).

JHB System

This layout, Figure 2-3, serves the role of removing nitrogen and phosphorus through nitrification-denitrification enhanced biological phosphorus removal (NDEBPR). It can be achieved through modification from the 5-stage Bardenpho layout where the secondary anoxic reactor of the later layout is shifted (van Loosdrecht *et al*., 2008) with a purpose of achieving N and P removal like the UCT system or through modifying the 3-Stage Phoredox (Figure 2-2) by adding passing the return sludge through an anoxic zone before it reaches the anaerobic zone (Stratful, *et al*., 1999).

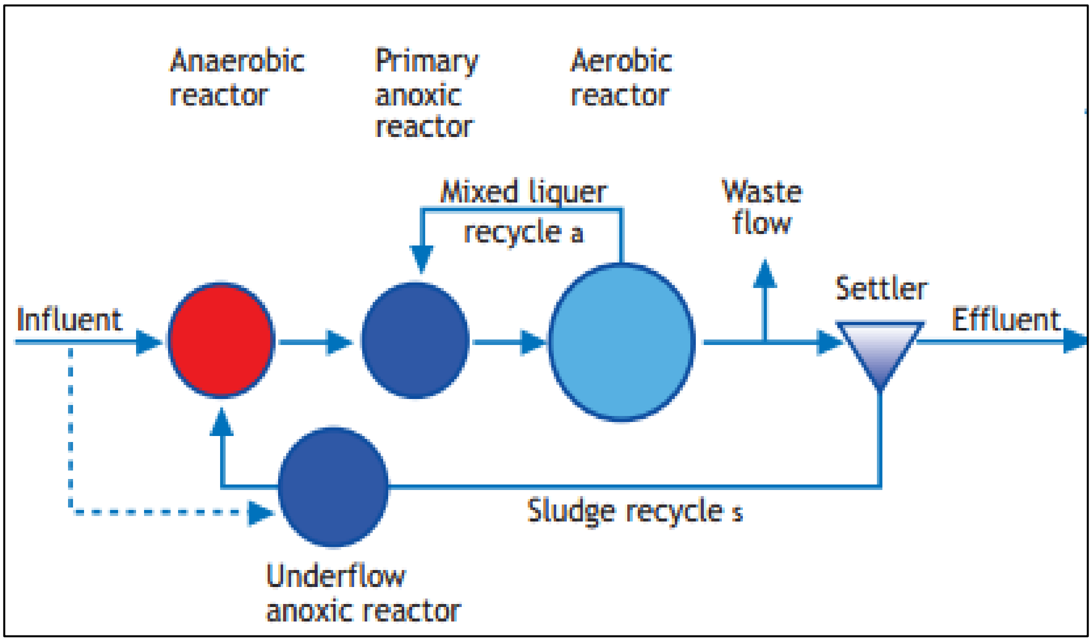

Figure 2-3: JHB configuration (van Loosdrecht *et al*., 2008)

According to Ekama (2017), though the JHB system has a smaller reactor volume than that of the UCT system (Figure 2-4), the balanced solid retention time (SRT) for lower effluent N and P concentration of the prior layout is longer than that of the later. Hence, JHB system produces more sludge than the UCT system. However, they both reach similar effluent N and P concentrations (Ekama, 2017).

UCT System

This UCT system is an NDEBPR configuration which achieves considerable removal of nitrogen and phosphorus nutrient from the influent wastewater. The activated sludge reactor is subdivided into three different compartments (Figure 2-4), namely, anaerobic, anoxic and aerobic zones. The sludge from the secondary settling tank (s-recycle) and mixed liquor (a-recycle) from the aerobic reactor are recycled into the anoxic reactor and a recycle flow (r-recycle) from the anoxic reactor to the anaerobic reactor.

The UCT layout is similar to the MLE system in that both systems do not achieve complete denitrification (Wu and Ekama, 2015) but differs in that the later one does not remove any phosphorus. Moreover, like the MLE system, the anoxic reactor from the UCT configuration has high denitrification rates which makes it possible to an 80% N-removal to be achieved; however, if both the MLE and UCT systems have the same unaerated mass fraction, the MLE will achieve more N-removal because part of the unaerated mass fraction for the UCT system will be in the anaerobic reactor.

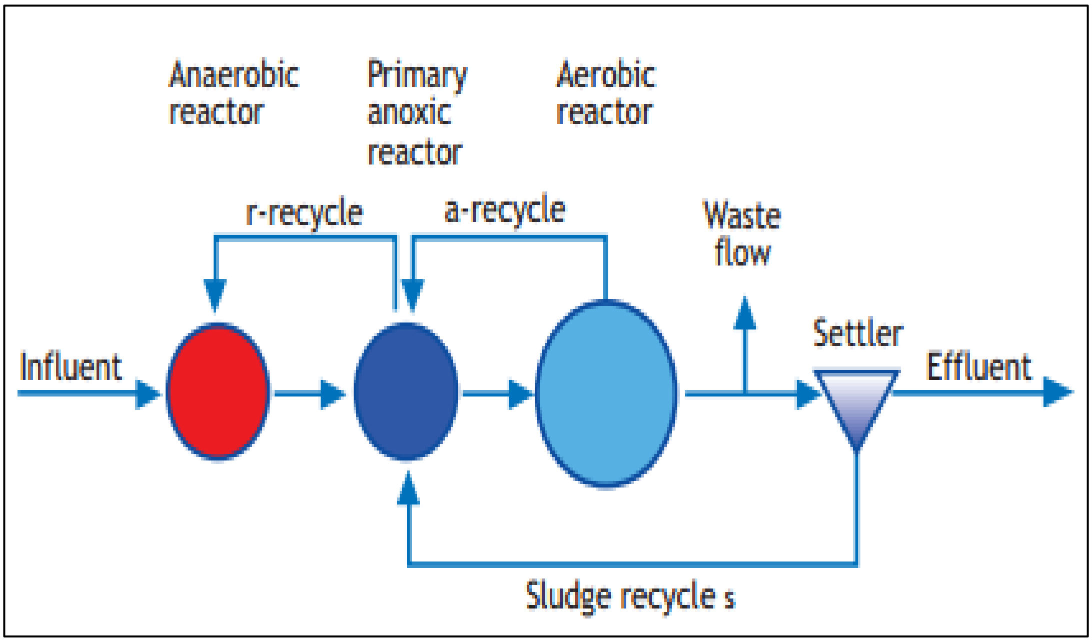

Figure 2-4: UCT configuration (van Loosdrecht *et al*. 2008)

2.1.2.3 Sludge Treatment

The main objectives of sludge treatment are to reduce its water content thus its volume; to reduce the fraction of active biomass in sludge; and to condition it such that it meets the sludge disposal regulations (Appels *et al*., 2008). Appels *et al*. (2008) further state that sludge treatment is important for the reduction of the operational costs of the plant as the disposal of sludge contributes up to 50% of the plant's operational costs. Sludge can be treated either by incineration, anaerobic or anoxic-aerobic digestion. The selection of the most appropriate type of sludge treatment to use is chosen based on the source of sludge production and whether biogas production is needed. Sludge production has two sources, namely, sludge produced from the primary sedimentation unit, i.e., primary sludge (PS), and sludge produced from the biological reactor, i.e., secondary sludge, also referred to as waste activated sludge (WAS). The PS accumulates at the bottom of the PST and consists of settleable solids removed from the influent wastewater; whereas WAS consists of biomass produced through the biological processes. The PS is usually more suited for biogas production in the anaerobic digester, due to its higher biodegradable fraction and lower portion of organically bound nutrients (the N and P usually get released during anaerobic digestion (AD) and end up in the dewatering liquor of the system; see Section below). The fraction of biodegradable organics in WAS depends on the system sludge age (a higher sludge age (Rs) results in lesser active fraction of biomass; Ekama, 2017). Moreover, the WAS biodegradables (i.e., biomass) usually have a larger organically bound N and P content than PS, hence is more suited to be treated in the anoxic-aerobic digester where the nitrogen removal can also take place with a breakdown of the organic material (Ekama, 2017, Vogts *et al*., 2015).

2.1.2.4 Dewatering Liquor Treatment

The recycling of sludge dewatering liquor (DWL) to the mainstream reactor has a negative impact on the plant performance (Ekama, 2017; Vogts *et al*, 2015, Solon *et al*, 2017). The DWL is produced from the anaerobic or anoxic-aerobic digestion of sludge and from sludge thickening processes such as gravity thickener and flotation tank. This liquor is generally recycled back to the upstream processes, however, recycling it to the mainstream process overloads the reactor as the ratio of the recycled N and P nutrients to the organics is very low. Consequently, the capacity of the plant to remove organics and nutrients is exceeded which results in poor effluent quality, unless a side-stream treatment process (SSTP) is incorporated in the system to reduce the concentration of N and P in the DWL.

The concentration of the DWL returned to the upstream process varies depending on the source of this liquor. The DWL produced from the anaerobic digestion of WAS contains high N and P content than that produced from the anaerobic digestion of PS (Vogts *et al*, 2015 and Ekama, 2017). According to Wentzel *et al*. (2007), biodegradable particulate organics (BPO) harvested in the PS contain approximately five times less N and P content compared to ordinary heterotrophic organisms (OHOs) and polyphosphate accumulating organisms (PAOs) that forms part of the biomass in WAS. Furthermore, WAS produced from an ND and NDEBPR systems contains approximately 2.5 times more N and P content than of PS. Consequently, treating WAS in the anaerobic digester produces high N and P concentrated DWL while the anoxic-aerobic treatment of WAS results in a low N and P concentration, less than 10 mgN/l and 20 mgP/l respectively (Vogts *et al*, 2015). Therefore, recycling the DWL from the WAS AD to the upstream process results in poor effluent quality unless a side stream treatment is considered (Ekama, 2017). In addition, this high N and P concentrated liquor results in phosphate precipitation in the pipe network which causes pipe blockages and loss of digester capacity (Vogts *et al*., 2015, Kazadi Mbamba *et al*., 2016). Ekama (2017) recommends that WAS should not be anaerobically digested unless P recovery is a requirement. The anaerobic digestion of the PS does not produce high N and P content in the DWL, hence recycling it back to the main treatment processes does not a remarkable impact on the effluent quality (Vogts *et al*, 2015 and Ekama, 2017).

2.1.3 Side-stream Treatment Processes

Side-stream treatment processes are used to decrease the concentration of N and P in the dewatering liquor before recycling it to the mainstream processes. Several modelling studies (Kazadi Mbamba *et al*., 2016, Solon *et al*., 2017 and Munch and Barr, 2011) have been conducted to evaluate the impact of integrating a side-stream process in the system, on the overall plant performance. It was found that there is a reduction in P concentration by 95% and 43% from the dewatering liquor and effluent respectively, using the benchmark simulation model No. 2-P which has an expanded framework of physicochemical framework (Kazadi Mbamba *et al*, 2016). In addition, N concentration in the dewatering liquor and effluent is reduced by 9% and 96% respectively through mineral precipitation (Solon *et al*, 2017) and 94% reduction in the P concentration in the dewatering liquor (Munch and Barr, 2011). The degree of reduction in N and P concentrations in the dewatering liquor depends on the type of side-stream process selected. The impact of integrating bio-augmentation batch enhanced (BABE) and struvite precipitation processes in full-scale treatment plant will be evaluated in the steady-state model that will be developed through this study.

2.1.4 Wastewater Characterisation

Influent wastewater data reconciliation is crucial so that the appropriate design and operation parameters can be selected. Plant-wide models are developed based on plant-wide mass balance to track down various elements such as carbon, hydrogen, oxygen, nitrogen and phosphorus (C, H, O, N, P) throughout the treatment plant (Wu and Ekama, 2015). Wentzel *et al*. (2006) summarise the benefits of plant-wide mass balance as:

- To trace the materials throughout the full-scale plant to ensure continuity;
- To identify the characteristics of the upstream and downstream flows between the different unit processes;
- To assess the impact of recycling liquors and sludge from a unit process into the subsequent units;
- To identify unit operation bottlenecks which affect full-scale WWTP operation;
- To enable WWTP unit process optimisation for maximum throughput with less impact on the effluent quality;
- To identify typical processes that will be needed based on the influent wastewater characteristics and the likelihood of mineral precipitation problems in the sludge treatment operations; and
- To assess the impact of adding other unit operations, such as SSTP, in the WWTP sequence on the plant performance.

For such a mass balance to be achieved it is important that the wastewater is characterised to identify the different influent wastewater constituents so that suitable operation and design conditions can be chosen for treating wastewater. The extent of wastewater characterization depends on the effluent quality specified, i.e., the stricter the quality of the effluent required, the more complex and sophisticated must the BNR system be to achieve the specified effluent quality, hence, the more complex the characterization (Ekama and Wentzel, 2008a).

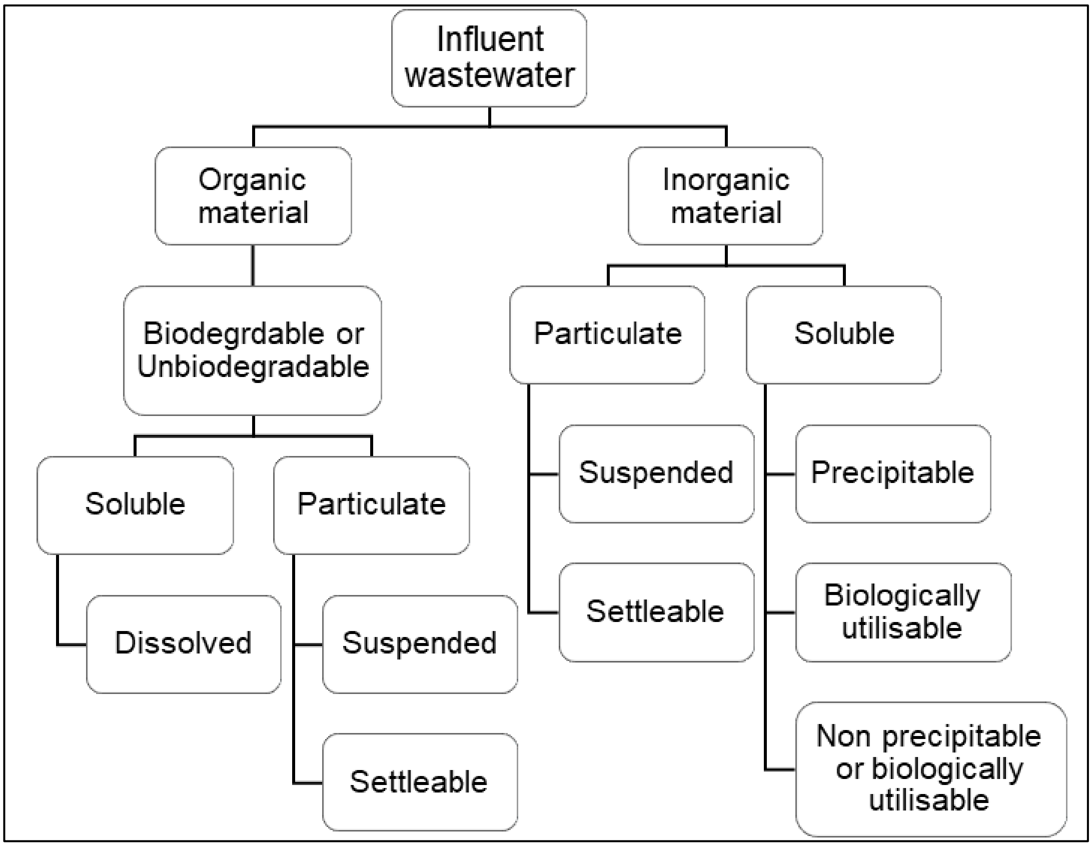

Figure 2-5: Influent wastewater subdivisions (Ekama and Wentzel, 2008a)

Influent wastewater is subdivided into organic and inorganic material as shown in Figure 2-5. Organic material consists of biodegradable and unbiodegradable organics. The knowledge of the influent biodegradable COD allows the designer to predict the how much oxygen will be used and the biodegradable load that will be produced so that the appropriate reactor sludge age may be selected (WRC, 1984). Biodegradable particulate organics (BPO), also referred to as slowly biodegradable COD (SBCOD) are not further subdivided. Biodegradable soluble organics (BSO), referred to as readily biodegradable COD (RBCOD), are further subdivided into volatile fatty acids (VFA) and fermentable readily biodegradable COD (F-RBCOD); both the VFA and F-RBCOD are important in the operation of the nitrification-denitrification enhanced biological phosphorus removal (NDEBPR) since these fractions responds differently under anaerobic conditions (Ekama and Wentzel, 2008a). The unbiodegradable organics i.e., particulate and soluble unbiodegradable organics, UPO and USO, respectively are not further subdivided. The inorganic material is subdivided into soluble fractions, namely free and saline ammonia (FSA) and orthophosphate (OP), and particulate (ISS) components (i.e., settleable or suspended). The influent organic constituents mass fractions are summarised in Table 2-2.

Table 2-2: Influent wastewater organic mass fractions (Ekama, 2017)

Group	**COD**	**C**	**H**	**O**	**N**	**P**	**Composition in $C_xH_yO_zN_aP_b$ (X=1)**				
Ratio	fcv	fc	fh	fo	fN	fP	x	y	z	a	b
VFA	1.067	0.400	0.0670	0.533	0.00	0.00	1.00	2.00	1.00	0.00	0.00
FBSO	1.420	0.470	0.076	0.427	0.017	0.010	1.00	1.942	0.681	0.030	0.008
USO	1.420	0.470	0.074	0.370	0.049	0.000	1.00	1.833	0.600	0.086	0.000
BPO	1.500	0.510	0.069	0.392	0.019	0.010	1.00	1.623	0.577	0.032	0.008
UPO	1.481	0.518	0.066	0.291	0.100	0.025	1.00	1.534	0.421	0.166	0.019

Influent wastewater data reconciliation plays a major role in the success of WWTP modelling. Rieger *et al*. (2010) state that the model results are as good as the input data. Data reconciliation at the treatment plant is a key element to achieving accurate model results. Plant-wide mass balance and wastewater characterisation outputs are compromised if the input plant data (i.e., plant measurements) is poor. It is, therefore, recommended that the process of data reconciliation should be done cautiously to avoid errors in flow measurements, analysis and sampling.

2.1.5 Plant Performance Evaluation

Wastewater treatment plant performance is evaluated by assessing the impact of the design and operational parameters of each unit process on the effluent quality and operational cost. There are several performance indices that are used for analysing the plant performance such as effluent quality index (EQI) and operational cost (OCI). The EQI is the weighted sum of the pollution loads that are leaving the plant. It is expressed as the sum of the total suspended solids (TSS), organic load expressed as chemical oxygen demand (COD), biochemical oxygen demand (BOD5), total Kjeldahl nitrogen (TKN) and all oxidised forms of nitrogen leaving the plant. The OCI consists of the major treatment plant operation costs such as aeration energy, pumping energy, mixing energy, sludge production, external carbon addition, methane production and net heating energy (Flores-Alsina, *et al*., 2014, Jeppsson *et al*., 2007). These plant evaluation indices will be integrated into the simple steady-state model that will be developed in this research.

2.2 Modelling of WWTP Processes

2.2.1 Background

Mathematical models are useful tools in the design and operation of WWTPs (van Loosdrecht *et al*., 2008). A model can be defined as a simplified version of a real object, system or process in which a key element of the behaviour or the characteristics of the actual system is replicated (Rieger *et al*., 2013). These models are developed based on assumptions and hypotheses with the aim of predicting the interactions between various physical, biological and chemical processes. The objectives of WRRF mathematical models can be summarised as (Wentzel *et al*., 2008; Gernaey, *et al*., 2004; Billing & Dold, 1988, Ikumi, 2011):

- Tools for evaluating and optimizing various processes by comparing the predicted results to the observed responses;
- Tools to provide information that is not obvious from pilot-scale studies;
- Tools for evaluating the various solutions that cannot be performed by pilot-scale and other studies;
- Tools to identify parameters that significantly influence the system response, thereby helping with establishing design criteria;
- For control diagnosis and monitoring the system to provide early warning to void system malfunction; and
- Educative tools into the WWTP processes.

Historically, WRRF models and simulation tools have been used by consulting engineers and researchers for process optimisation and research. However, there has been a growing interest in using these tools by different stakeholders such as municipalities, plant operators and decision-makers, who have limited technical expertise of the processes incorporated in those tools.

Stakeholders use these tools primarily to help them make better decisions with regards to capital cost and operational costs of WRRFs to meet the ever-rising stringent effluent qualities set in place by a water affair department (Lizarralde *et al*., 2018). Additionally, these simulation tools help them make wise justifications for capital improvement of the plant, plant optimisation with respect to chemical or energy use, type of treatment process to be used, etc. (Menniti *et al*., 2018). The success of these tools is dependent on how easily they can be used by these new stakeholders. Therefore, it is very important that these simulation tools should be simplified so that they can be used by the new stakeholders (Section 2.3.4).

2.2.2 Modelling Methodologies

There are key elements in successfully developing WRRF models. These include, but are not limited to, obtaining reliable measurements, the selection of key characteristics and behaviour, the use of simplified approximations and assumptions, the accuracy of simulation output and the reliability of the predictions (Rieger *et al*., 2013). It is important to note that it is impossible to develop a model that describes all processes and compounds. Therefore, the art of model development is to identify which process and compounds are significant and to eliminate those that have minimal impact on fulfilling its objectives (van Loosdrecht *et al*., 2008).

2.2.2.1 Black-box and White-box Models

There are two extremes that are considered in mathematical model development, namely, empirical and mechanistic principles (van Loosdrecht *et al*., 2008). The empirical models are developed based on the recognition of key parameters that describe the process of interest, and by linking this relationship with observations. These models are referred to as black-box models because they are developed based on observations although mechanisms and processes are either ignored or not known. On the contrary, mechanistic models are developed based on the conceptualisation of system biological and physical mechanisms and operations. These are referred to as glass box or white-box or deterministic models because they describe, to a detailed and in a scientifically sound way, the system processes that lead to the predictions generated (Gernaey *et al*., 2004). Gernaey *et al*. (2004) summarise several steps involved in developing mechanistic models.

- The first step in developing a mechanistic model is to describe the purpose and application of the model to be developed. This step provides the scope in which the developed model can work.
- Secondly, the system operating process and compounds on which these processes act is identified. The recognition of the interactions between the system processes and compounds is used to formulate kinetic and stoichiometric equations which are used in the mechanistic models.
- The hydraulics model of the WWTP or WWTP tanks is determined.
- Wastewater and biomass characterization are done.
- The data is reconciled to the steady state model. This is achieved by comparing the model prediction to the observations.
- The developed model is calibrated and validated to ensure that the developed model is predicting a representative of the actual system.
- Once the model has been developed, various scenario evaluations can be done.

Both empirical (black-box) and mechanistic (white-box) models have functional limitations (van Loosdrecht *et al.*, 2008). Empirical models are functional only within the boundaries (i.e. wastewater characteristics, system parameters) in which they were developed, and no extrapolation can be reliably attempted because of their black-box nature. On the other hand, although white-box models are widely applicable, and extrapolation can be done to some extent; however, caution should be taken while applying these models outside the boundaries within which they were developed. Gernaey *et al*. (2004) mention further limitations in white-box models. Firstly, they do not provide accurate predictions when there is not enough data for model calibration. Secondly, they are less accurate in describing activated sludge floc structure, which in full-scale results in simultaneous nitrification and denitrification. Thirdly, they are limited in describing the full-scale sedimentation process. Lastly, these models do not provide accurate results during rain events because they are generally calibrated for dry weather situations. Such limitations in mechanistic models lead to the need for other modelling methodologies.

2.2.2.2 Hybrid Models

There are alternative methodologies in WRRF modelling aimed to mitigate the limitations of the most widely used white-box models. Besides the black-box modelling, the most common alternative modelling methodologies are the combination of white-box with black-box models to form hybrid models. These models are formed based on first engineering principles (white-box characteristic), where specific functionalities (i.e., reaction kinetics) must be estimated or where process knowledge required to construct white-box models is limited (Gernaey *et al*., 2004). Furthermore, black-box models are used to provide data predictions where white-box models are either not valid or do not accurately describe WWTP processes i.e., black-box models can be used to compensate for the limitation of white-box models in describing the sedimentation process. In this case, a black-box model would be developed specifically for the sedimentation process, and it would, therefore, be useful in indicating sedimentation problems so that appropriate measures can be taken in time. Therefore, the functional limitation of both white-box and black-box models are compensated by producing a hybrid model.

2.2.3 Steady-State Models

Steady-state models are simple WWTP models developed, based on the stoichiometry and rate-limiting kinetics of the system processes. They are often used to determine the system design parameters to meet a specified performance criterion such as effluent quality (Wentzel, *et al*., 2006). Wentzel, *et al* (2006) summarises the main uses of steady-state models as for:

- Rapid, simple and easy estimation of system design and operational parameters such as reactor volume, sludge age, recycle ratios, and oxygen utilisation for a specific design standard,
- Investigating how sensitive the performance of the system is to the operational and design parameters,
- Estimating the upstream products which are used as inputs for downstream processes, and
- Provide a reference for cross-checking validated plant-wide model of South Africa (PWM_SA) simulation output results.

2.2.4 Dynamic Models

Dynamic models are complex models that use varying flows and loads to evaluate the time-dependent response of the plant due to dynamic loading conditions (Ekama and Wentzel, 2008a). Ikumi (2011) further summarises the use of these models as:

- For sensitivity analysis of the model application and assessment of various operation strategies.
- Enabling accurate sizing of the different unit processes and the selection of the best design alternative for the optimum plant performance criteria i.e., effluent quality and operation cost.
- Dynamic model tools can be used to provide training to plant operators with respect to the implication of operating conditions on the overall plant performance.

2.3 Existing WRRF Models

2.3.1 Introduction

Historically, wastewater treatment plant modelling has been done for single unit processes. The WWTPs consist of single-unit operations that are interconnected through a series of flows where the outputs from an upstream unit process become an input for the downstream process (Wu & Ekama, 2015). Therefore, it is important that each single unit process is well optimised and designed so that it will not be detrimental on the downstream processes thus impacting the overall plant performance (Wentzel, *et al*., 2006). However, single-unit modelling limits the evaluation of the interactions between upstream and downstream processes over the whole plant. Consequently, this isolation in modelling a single unit process leads to incompatibilities and difficulties in the design of treatment plants, hence full-scale modelling is an advantage (Wu and Ekama, 2015).

For the past 15 years, there has been a shift from modelling WWTPs from a single unit to full-scale models. Full-scale WWTP models provide a platform to study the interactions between different processes along the treatment line and their impact on the overall plant performance (Kazadi Mbamba *et al*., 2016, Ekama, 2017). Several plant-wide steady-state models such as the mass balance spreadsheet developed by Sötemann (2005) and Ekama (2009) have been developed and are useful in the development of design and operation WWTP tools such as that of Wu and Ekama (2015). These steady-state models contain a comprehensive description of wastewater characterisation and unit processes (Ikumi, 2011). For the sake of this project under consideration, the plant-wide model that will be considered in this study is a replica of typical South African WWTP configuration consisting of sedimentation units (i.e., PST and SST), biological activated sludge reactor and anaerobic digestion. The main unit processes that will be evaluated within this model are sedimentation in PST (influent wastewater characterisation), organism growth and decline, and the biological nitrogen and phosphorus removal (Section 2.3.3). The impact of these unit processes on the overall full-scale plant performance will be assessed.

2.3.2 Activated Sludge Models

The IWA task group developed several activated sludge models (ASM) that would be used as benchmark simulation models. The Activated sludge model No. 1 (ASM1) developed by Henze *et al*. (1987) is considered as a reference to other ASM models such as ASM2, ASM2d and ASM3. It was developed primarily to describe the biological nutrient removal (organic material and nitrogen) and sludge production in municipal wastewaters (Gernaey *et al*., 2004). Gernaey *et al*. (2004) summarise the ASM1 model assumes as:

- The kinetic model parameters are temperature dependent, therefore model calibration for a specific temperature is needed;
- The pH is constant or remains near neutral;
- All nitrification inhibitory toxins are calibrated in the nitrification parameters;
- The wastewater composition originates from municipal wastewater. However, if industrial wastewater is to be treated, the model equations (especially for nitrification) are changed to cater for industrial waste.
- The nitrification process is a one-step process (i.e. conversion of FSA to nitrate) if there is a low concentration of nitrite in the WWTP.

The activated sludge model No. 3, ASM3, (Gujer *et al*., 1999) was developed with the aim of removing nitrogen from the wastewater but with improving defects in the ASM1 (Gernaey *et al*., 2004). It recognises polymer storage in the heterotrophic sludge which is not considered in ASM1. Furthermore, ASM3 is easier to calibrate compared to ASM1. The activated sludge model No. 2, ASM2, (Henze *et al*., 1995) incorporates biological phosphorus removal. The ASM2d (Henze *et al*., 1999) was developed to add to the ASM2 model the denitrifying effect of PAOs. For more details about ASM development refer to Gernaey *et al*. (2004). Table 2-3 summarises some of the activated sludge models that have been developed over the years and the principles upon which they function.

Table 2-3: Review of activated Sludge Model (ASM) family developed over the years (Gernaey *et al*., 2004)

Model	Nitrification	Denitrification	Heterotrophic/ autotrophic decay	Hydrolysis	Bio-P	Den. PAOs	Lysis of PAO/PHA	Fermentation	Chemical P removal	Reactions	State Variables	Reference
ASM1	X	X	DR, Cst	EA						8	13	Henze *et al*. (1987)
ASM3	X	X	ER, EA	Cst						12	13	Gujer *et al*. (1999)
ASM2	X	X	DR, Cst	EA	X		Cst	X	X	19	19	Henze *et al*. (1995)
ASM2d	X	X	DR, Cst	EA	X	X	Cst	X	X	21	19	Henze *et al*. (1999)
B&D	X	X	DR, Cst	EA	X	X	EA	X		36	19	Barker &Dold (1997)
TUDP	X	X	DR, Cst	EA	X	X	EA	X		21	17	Brdjanovic *et al*. (2000)
ASM3-bio-P	X	X	ER, EA	Cst	X	X	EA			23	17	Rieger *et al*. (2001)

Where Den PAO = Denitrifying PAO activity included; DR = Death regeneration concept;

EA = Electron acceptor depending; ER = Endogenous respiration concept; and Cst = Not electron acceptor depending.

2.3.3 UCT Models

The University of Cape Town-based research group developed an aerobic steady-state (AS) model with the aim of removing organics and nitrogen nutrients from wastewater (Ikumi, 2011). In these models, the influent biodegradable and unbiodegradable organics, and nitrogen and phosphorus nutrients are removed from wastewater through various processes described in Section 2.1.2. Soluble unbiodegradable organics escape with the effluent while the particulate unbiodegradable organics are either removed through the primary sedimentation process or through the waste flow rate (Q_w). It has been observed that provided the sludge age is longer than 3 to 4 days (Ekama and Wentzel, 2008a) the concentration of both readily and slowly biodegradable organics (i.e., soluble and particulate biodegradable organics, respectively) in the effluent is very small. Therefore, this model was developed on the assumption that biodegradable organics are completely used by ordinary heterotrophic organisms (OHOs, Section 2.3.3.1) in the biological reactor to form biomass (i.e., organism growth process is complete; hence, the kinetics of biomass growth can be ignored). However, the death process is slow (i.e., does not reach completion, even at long sludge ages), therefore, the kinetics of biomass death (endogenous respiration) are incorporated into the steady-state model of Marais and Ekama (1976). Organism growth and death model in the AS model are further described further below.

2.3.3.1 Organism Growth and Decline

The biological behaviour of the organism is modelled based on two processes, namely growth and endogenous respiration (Ekama and Wentzel, 2008a). Ordinary heterotrophic organisms (OHOs) use biodegradable organics to generate more cell mass. A fraction (the yield, YH) of the biodegradable organics expressed in terms of chemical oxygen demand (COD) is used for cell mass generation (anabolism) while the remainder (1-YH) is used for energy production (catabolism) that is needed in the anabolic and other cellular processes. Monod (1949) studied the growth behaviour of organisms when a substrate is limited while nutrients i.e., N. P and O are provided in abundance. The organism growth rate can be expressed by Monod kinetics (Equation 2-1).

$$\mu = \frac{\mu_m . S_b}{K_s + S_b} \qquad 2\text{-}1$$

Where μ = specific growth rate of organisms (g/g.d); μ_m = maximum specific growth rate (/d); K_S = substrate half maximum saturation coefficient (mgCOD/l.); and S_b = concentration of biodegradable organic material (mgCOD/l).

The death of biomass is modelled according to the theory of endogenous respiration (Henze *et al*, 2008). Endogenous respiration (Figure 2-6) is a process through which a portion of the active biomass (i.e., 24%) degenerates. A part of the dead biomass (i.e., 80%) is deemed biodegradable and is used catabolically to provide energy (oxygen is consumed in the process), while the remaining fraction (20%) is unbiodegradable material known as the endogenous residue. The endogenous residue accumulates in the reactor as part of volatile suspended solids and is removed with the waste sludge (i.e., essentially remains in the system for the sludge age duration).

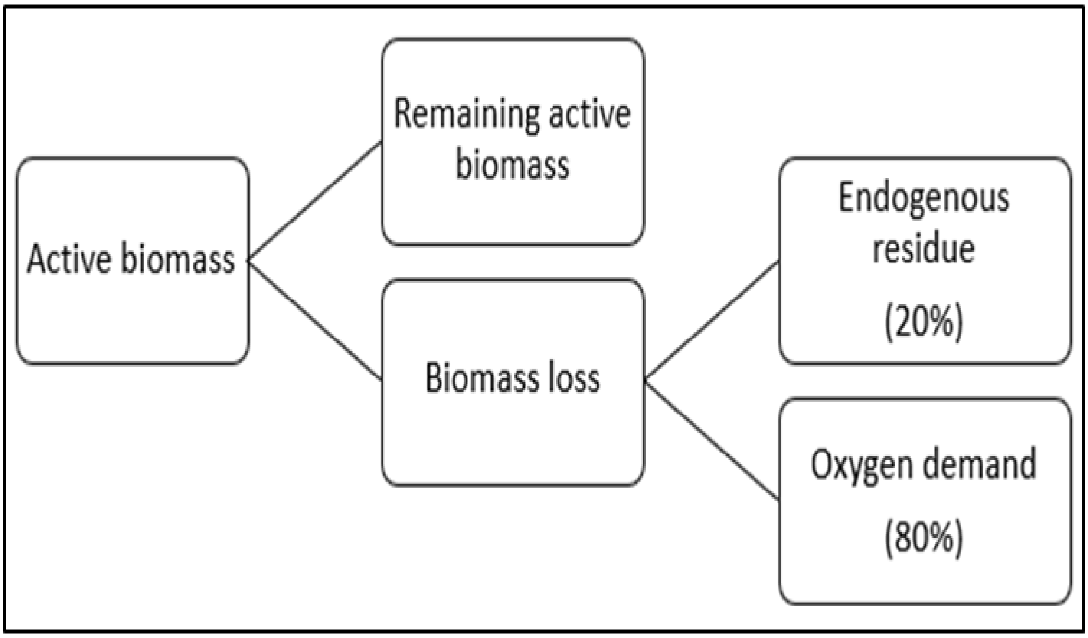

Figure 2-6: Endogenous respiration process

The concentration of endogenous residue in the reactor is predicted using Equation 2-2; and the oxygen consumed during the endogenous respiration, namely, carbonaceous oxygen utilisation rate (O_c) is calculated using Equation 2-3 of the steady-state activated sludge model (Henze *et al*., 2008).

$$X_E = f_{cv} f b_H X_H \tag{2-2}$$

$$Oc = f_{cv}(1-f) b_H X_H \tag{2-3}$$

Where X_E = endogenous residue (mgVSS/l); fcv = COD/VSS ratio of the organism organics (mgCOD/mgVSS); f = unbiodegradable fraction of OHOs; b_H = endogenous respiration rate (/d); and Oc = carbonaceous oxygen utilisation rate (mgO_2/l.d).

2.3.3.2 Nitrification Model

Nitrification is a biological process through which free and saline ammonia (FSA) is oxidized into nitrite and nitrate by autotrophic nitrifying organisms (Ekama & Wentzel, 2008b). This process happens through two sequential processes; firstly, ammonia-oxidizing organisms (ANOs) convert FSA to nitrite (Equation 2-4), then nitrite-oxidizing organisms (NNOs) converts nitrite to nitrate (Equation 2-5).

$$NH_4{}^+ + {}^3/_2\, O_2 (ANOs) \rightarrow NO_2{}^- + H_2O + 2H^+ \tag{2-4}$$

$$NO_2{}^- + {}^1/_2\, O_2 (NNOs) \rightarrow NO_3{}^- \tag{2-5}$$

The steady-state nitrification model for the growth process is based on two assumptions. Firstly, autotrophic nitrifying organisms use ammonia and nitrite for energy requirements (catabolism) and a fraction of ammonia for the synthesis of nitrogen cell mass. This implies that nitrifying organisms act as catalysts for nitrification, i.e., the synthesis of nitrogen is neglected because a small fraction (1%) of ammonia is nitrified to nitrate by the nitrifiers. Secondly, it is assumed that ANOs converts ammonia directly into nitrate. This assumption is valid because the rate of conversion of ammonia to nitrite by ANOs is slower than the rate of conversion of nitrite to nitrate by NNOs. Therefore, any nitrite that is available will be directly converted to nitrate if there are no NNOs inhibit compounds at the treatment plant (Ekama & Wentzel, 2008b). Consequently, the kinetics of ANOs are only considered in the steady-state model. In conclusion, these two assumptions imply that the rate of the conversion of ammonia is equal to the rate of nitrate formation (Equation 2-6).

$$\frac{dN_a}{dt} = \frac{dN_n}{dt} = \frac{1}{Y_A}\frac{\mu_{aMt}N_a}{K_{nT} + N_a}X_{BA} \qquad 2\text{-}6$$

Where N_n = nitrate concentration ($mgNO_3$-N/l); μ_{aMt} = maximum specific growth rate (mgANOVSS/mgANOVSSS/d); N_a = ammonia concentration (mgN/l); K_{nT} = half saturation constant; Y_A = yield coefficient of the nitrifiers (mgVSS/mgN); and X_{BA} = ANO concentration (mgANOVSS/l).

The endogenous respiration of ANOs is modelled the same way as that of OHOs. However, the endogenous respiration rate for OHOs (b_H =0.24/d) is much higher than that of ANOs (b_H = 0.04/d). The oxygen utilisation rate for nitrification (O_n) is 4.57 mgO/mgN (Equation 2-7), but it decreases to 4.3 mgO/mgN if FSA used for the synthesis of cell mass is taken into consideration.

$$O_n = 4.57\frac{dN_a}{dt} = 4.57\frac{dN_n}{dt} \qquad 2\text{-}7$$

Where dN_a = ammonia utilisation rate (mgN/l); dN_n = nitrate utilisation rate ($mgNO_3$-N/l); and O_n = nitrification oxygen utilisation rate (mgO_2/l.d).

2.3.3.3 Denitrification Model

Denitrification is a process through which excess nitrate is converted into nitrogen gas. Nitrification precedes denitrification; hence, it is recommended that for systems designed for nitrification (aerobic), an unaerated compartment should be added so that the aerobically generated nitrate can be denitrified to reduce its concentration in the effluent. Therefore, the denitrification process results in lowered effluent nitrate concentration. In addition, this process is beneficial for the recovery of alkalinity and reduction in oxygen demand (i.e., for every 1 mg of NO_3 denitrified, there is an increase of 3.57 mg alkalinity as $CaCO_3$ and 2.86 mgO of oxygen is recovered) (Ekama & Wentzel, 2008b). The main goal in designing for denitrification is to determine the concentration of substrate that is needed to denitrify the generated nitrate, given the anoxic mass fraction of biomass and the rate of nitrate flux into the anoxic zone. There are three sources of the substrate that is used in the denitrification process, viz. influent readily biodegradable COD (RBCOD), influent slowly biodegradable COD (SBCOD) and SBCOD generated by biomass through endogenous respiration. The denitrification model was developed based on the kinetics of the conversion of nitrate to nitrogen gas using the available substrate.

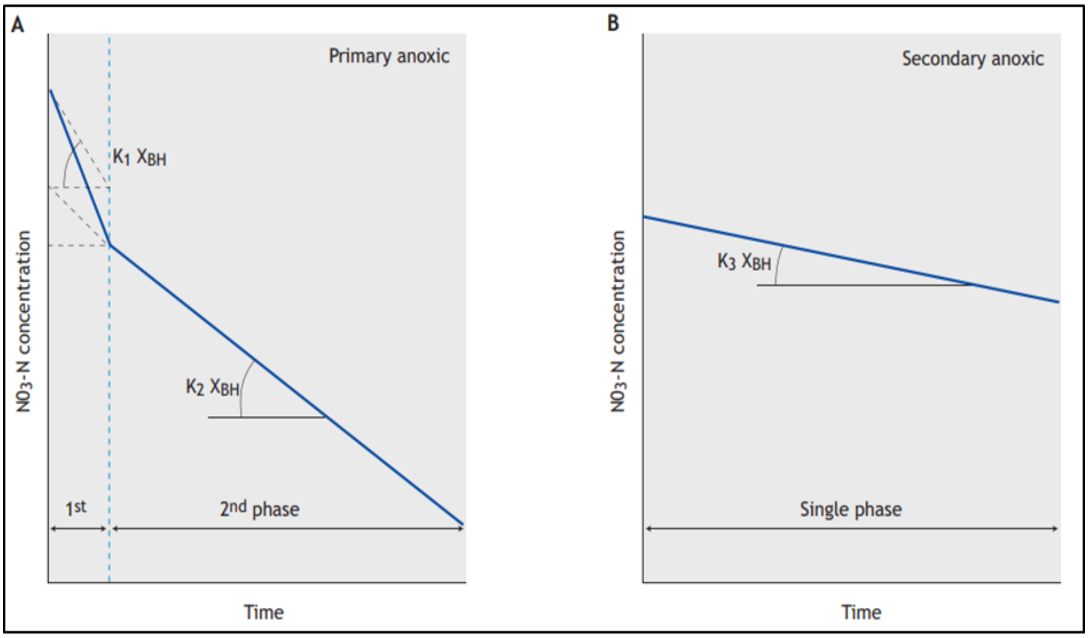

Figure 2-7: Denitrification rates in the primary and secondary anoxic plug flow reactors (Ekama and Wentzel, 2008b)

The steady-state denitrification model was developed based on the observation made with respect to the impact of the type of organics present on the denitrification process. The RBCOD is degraded at a faster rate than SBCOD because they have a smaller particle size. The denitrification process in the primary anoxic reactor happens through two subsequent phases; the first phase occurs rapidly compared to the second phase because it is controlled by the utilisation of influent RBCOD and SBCOD (K_1 and K_2), while influent SBCOD only is used in the second slow phase (K_2). The denitrification rate (K_3) in the secondary anoxic reactor is governed by the utilisation of SBCOD generated from biomass death (endogenous respiration). This phase is slower than the second phase in the primary anoxic reactor (K_3 = 2/3 K_2) due to the slower rate of endogenous respiration (Figure 2-7).

2.3.3.4 Biological Excess Phosphorus Removal Model

The biological excess phosphorus (P) removal is achieved through P uptake and P release processes that are facilitated by polyphosphate accumulating organisms (PAOs) (Figure 2-8).

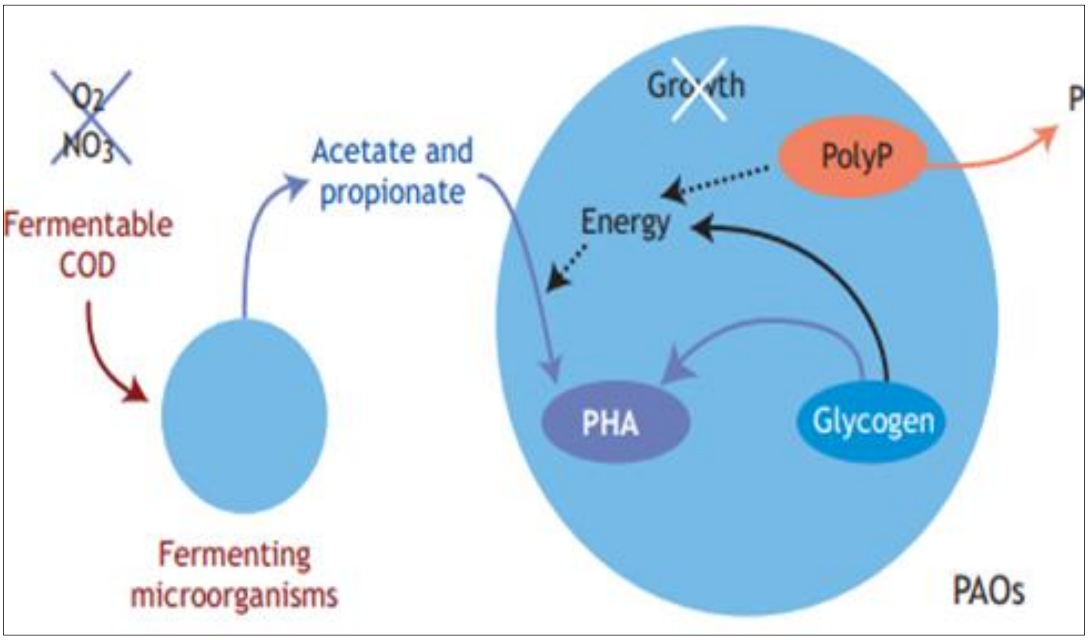

Figure 2-8: Biological excess P removal through P uptake and release facilitated by PAOs (Wentzel *et al*., 2008)

This process is maximized in several ways, including creating an anaerobic zone which favours the growth of PAOs and avoiding the recycling of oxygen and nitrate into this zone. In the anaerobic zone, OHOs that co-exist with PAOs ferment influent RBCOD into volatile fatty acids (VFAs). The PAOs then take up the VFAs and convert them to an energy-rich organic compound, that they store internally, known as poly- β-hydroxyalkanoates (PHA). The energy for the for PHA formation is obtained with the breakdown of PAOs internally stored polyphosphate (PP) which results in the release of orthophosphates and metals (which make up the PP) in the bulk solution. In the subsequent aerobic or anoxic zone, PAOs use the internally stored PHA for cell growth and energy generation (for cellular activities, including the P uptake from the bulk solution to form PP). The P removal is the difference between the P uptake, in the aerobic/anoxic zone, and P release in the anaerobic zone.

The biological excess P removal model is based on the principles of allocating substrate between PAOs and OHOs for their growth. Once the fraction of influent biodegradable COD has been allocated to the organisms, their mass can be determined. With the knowledge of the P content in each mass, the overall P removal is the sum of the P removal achieved by each individual organism (via active and inert biomass waste) and the P removed through the influent accumulate inorganic matter (Wentzel *et al*,.2008).

2.3.3.5 Anaerobic Digestion Model

Sötemann *et al*. (2005) developed a steady-state anaerobic digestion (AD) model based on COD, N and P mass balance to model the anaerobic digestion of sludge. The AD of sludge is facilitated by three or four types of organisms depending on the hydrogen partial pressure (pH_2) (Figure 2-9). For low pH_2 i.e., at equilibrium, three organisms are involved in the AD process. (i) Acidogens convert complex organics (biodegradable COD) into acetic acid (HAc) and H_2 through a process known as acidogenesis. Organically bound nitrogen in the biodegradable COD is released as ammonia (NH_3), which then reacts with a hydrogen ion to form ammonium (NH_4^+). (ii) Acetoclastic methanogens then convert HAc to methane (CH_4); this process releases CO_2 in the gaseous phase. (iii) Hydrogenotrophic methanogens convert H_2 to CH_4. For high pH_2, acidogens produce also propionic (HPr) and other volatile fatty acids (VFAs). Then, acetogens, another group of organisms, convert HPr to HAc and H_2. The hydrogenotrophic methanogens then convert H_2 to CH_4.

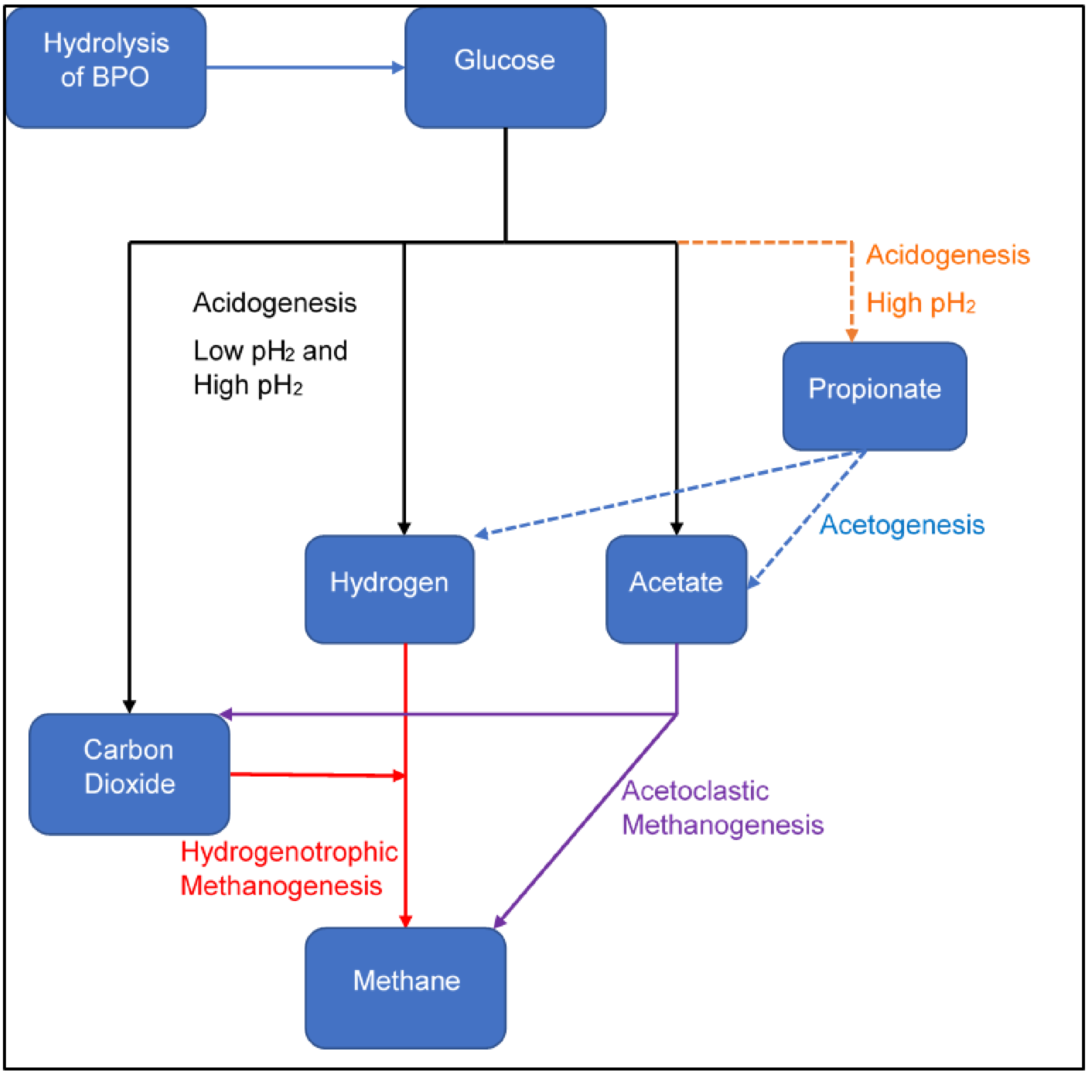

Figure 2-9: Schematic representation of the anaerobic digestion process (Ikumi, 2011)

The digester pH has to be maintained at neutral (7-8) to ensure optimum operation. This is achieved by controlling the concentration of HAc in the system. The HAc concentration increases either when there is a high load of organics coming to the digester than that which can be treated or when there is a methanogen inhibitor in the influent. It is, therefore, important that the acetogens and acetoclastic methanogens use up HPr and HAc, respectively to maintain neutral pH. Therefore, since the hydrolysis/acidogenesis process is the slowest process and has an impact on the pH of the digester i.e., monitors the production of HAc from the organics, the kinetics of this organism is considered in the AD model. Furthermore, since all other processes are fast (i.e., reaches completion within a short time), it is also assumed that the acidogenesis produces biomass, CH_4, water and CO_2. Consequently, the Sötemann *et al*. (2005) AD model consists of three parts: (i) the kinetic model which aims at determining the rate of biodegradable COD utilisation and methane gas (CH_4) production for a given sludge age; (ii) the stoichiometric model which aims at determining the concentration of ammonium (NH_4^+) and alkalinity generated; and the gas composition of the fraction of the COD removed; and (iii) a weak acid/base chemistry model, from which the pH of the anaerobic digester is established based on the partial pressure of CO_2 and alkalinity generated. The stoichiometric model determines the concentration of the AD products i.e. CH_4, biomass growth (which is very negligible) and NH_4^+ ensuring elemental (C, H, O, N) mass balance. The stoichiometric non-COD products (NH_4^+, HCO_3^-, and CO_2) are used to determine the weak acid/base chemistry; CH_4 and CO_2 set the partial pressure of CO_2 (p_{CO2}) and together with HCO_3^-, they establish the AD pH.

2.3.4 WRRF Model Simplification

Based on the above discussions, WRRF models have been developed primarily to be used by technically adequate professionals or researchers. Consequently, the currently developed models cannot be used by those who do not the technical expertise and knowledge of the biological and chemical processes that happen in these models. However, due to a recent growing interesting in using these models by technically incompetent stakeholders, it is important that these models should be simplified to increase their uptake by this new group of users. In fact, the question of WRRF model simplification has been at the centre of discussion among modellers. For instance, in a recent debate about the issue of simplicity versus the complexity of these models at the WWTmod2016, 56 % of modellers voted for developing more complex models, while 44% voted against such models (Lizarralde *et al*., 2018). Some of the concerns that were raised, in the discussion about the complexity and applicability of wastewater treatment plant simulation models, are:

- How complex should these models be and yet applicable?
- Can we trust the results from these models?
- Can these complex models be calibrated for practical use?

- How much information can these models provide?

Developing easy-to-use WRRF models with trusted outcomes (results) is not an easy task. Besides issues raised around the complexity of steady-state models, there are more challenges that must be overcome, such as the limited technical knowledge of the stakeholder and lack of confidence in the model outcomes, to develop such simplified models. Menniti *et al.* (2018) recommend that to overcome such challenges, the modeller should work closely with the involved stakeholders and that the accuracy of the model outcome should be made clear in the development stage of the model. Furthermore, stakeholders should be trained on how to use the models where necessary. Table 2-4 summarises some considerations that are important in developing simple models that can be used by those who have limited knowledge in modelling.

Table 2-4: Key considerations for developing simple modelling tools

Consideration	Reference
A new source of obtaining reliable results	Rieger *et al*., (2013) and Lizarralde *et al*., (2018)
Tool for selecting key process parameters and providing a description of the parameters and processes	Lizarralde *et al*., (2018)
Friendly user interface	Lizarralde *et al*., (2018)
Tools for parameter calibration	Lizarralde *et al*., (2018)
Data validation and calibration of the results	Rieger *et al*., (2013) and Lizarralde *et al*., (2018)
Provide information about the reliability of the results	Rieger *et al*., (2013)
Use of simplified approximations and assumptions	Rieger *et al*., (2013)
Have guidelines to help navigate the tool	Lizarralde *et al*., (2018)

2.4 Closure

There have been two major recent shifts in the design and operation of WWTPs in the past 20 years. Firstly, there has been a shift to consider WWTPs as water and resource recovery facilities

(WRRFs); this shift was motivated by the realisation that WWTPs do not only consume a large number of resources but that they also have a potential of recovering resources such as water, minerals and energy. Secondly, there has been a recent interest in using WRRF models by stakeholders i.e., plant operators, designers and supervisors who have limited modelling experience and technical expertise of the processes taking place in WWTPs. The stakeholders use these models for education on the relevant system processes and parameters and to help them during decision making for optimum design and operation. These two shifts have influenced the way WRRF models are being developed.

Historically, complex WRRF models have been used by consulting engineers and researchers for design, process optimisation and to study interactions between various biological and chemical processes in WWTPs. Several single unit operation and plant-wide models have been developed, the latter being of more interest because they enable the study of the interaction between the different unit process. The challenge with the currently developed simulation tools is that they are too complex and unrelatable to be used by the stakeholders. Furthermore, the current available plant-wide dynamic simulation tools take long to generate the data. Therefore, based on these challenges, it is the aim of this research project to develop a simple WRRF simulation tool that can be taken up and used by the new stakeholders for resource recovery at WWTP without compromising the outputs.

The developed WRRF tool will be used to evaluate the impact of recycling sludge dewatering liquors on the overall WWTP performance in the South African context; additionally, it will recommend the best SSTP appropriate for the performance of the plant. Return sludge dewatering liquors overloads the mainstream process with nutrients; consequently, exceeding the capacity of the plant to remove the nutrients without additional organics, consequently, poor effluent quality and high operation costs. There are several plant performance indices such effluent quality and operational cost indices, EQI and OCI respectively, that are used to assess the performance of the plant-based on the design and operation parameters. These performance indices, in addition to the SSTP will be incorporated in the developed WRRF tool with the aim that agreeable results can be generated to help stakeholders in making educated decisions in the design and operation of WWTPs.

3. Methodology

3.1 Introduction

This project was based on implementation of mathematical models as tools for evaluating water and resource recovery facilities. Hence the model implementation described in the three main sub-sections below, namely, (i) implementation of simplified steady state model, (ii) steady-state model comparison and (iii) case studies, which describe and justify the methods that were chosen to carry out the research project.

Section 3.2 describes the steps that were used with the aim of fulfilling the first objective (Section 1.5.1) through making various simplification of the plant-wide steady-state model of (Section 2.3 for description of this model) in order to increase its uptake by various stakeholders without compromising the results. This simplification process was done in the following stages: (i) An influent probabilistic fractionator (Section 3.2.1) was developed with the aim of reconciling influent wastewater data, (ii)The various wastewater treatment plant (WWTP) unit process models for steady-state conditions were interconnected where outputs from the upstream process became inputs for the downstream process with the intent of replicating full-scale operations (Section 3.2.2), (iii) A user-friendly interface of the simplified plant-wide steady-state model was developed to show the transition from complex models to the user-friendly engineering tools (Section 3.2.3), (iv) various steps were taken to ensure that there is confidence in the tool outputs (Section 3.2.4). Such steps include the model verification (using material mass balances to check internal consistency), fractionator sensitivity analysis and validation; and comparing the steady state results with the dynamic simulation model. Sections 3.2.5 and 3.2.6 discuss the side-stream treatment processes (SSTP) and plant performance evaluative indices, that were incorporated in the developed tool, respectively, to evaluate the impact of recycling dewatering liquor (DWL) to the activated sludge (AS) system.

The second objective (Section 1.5.2) was investigated by comparing the results from the developed tool (i.e., PPET) to those of validated steady-state models (Ekama, 2009) (Section 3.3). The aim of this comparative study was to investigate whether there are discrepancies between the results generated by both simulations when both models are run under the same steady-state conditions.

Section 3.4 describes the design and operation conditions of three full scale WWTPs that were used in the case studies. The purpose of these case studies is to investigate the third objective of this research (Section 1.5.3). For the scope of this project, the only design and operation question that this research will try to answer is: is there any added benefit of integrating SSTP in the full-scale South African wastewater treatment plants? This question was investigated through using the developed simplified steady-state simulation tool to run case studies on South African WWTPs. The SSTP and plant performance operation indices that were used in this investigation have been developed in a parallel study. Figure 3-1 summarises the process of the model simplification from data reconciliation (fractionator) to the plant performance evaluation.

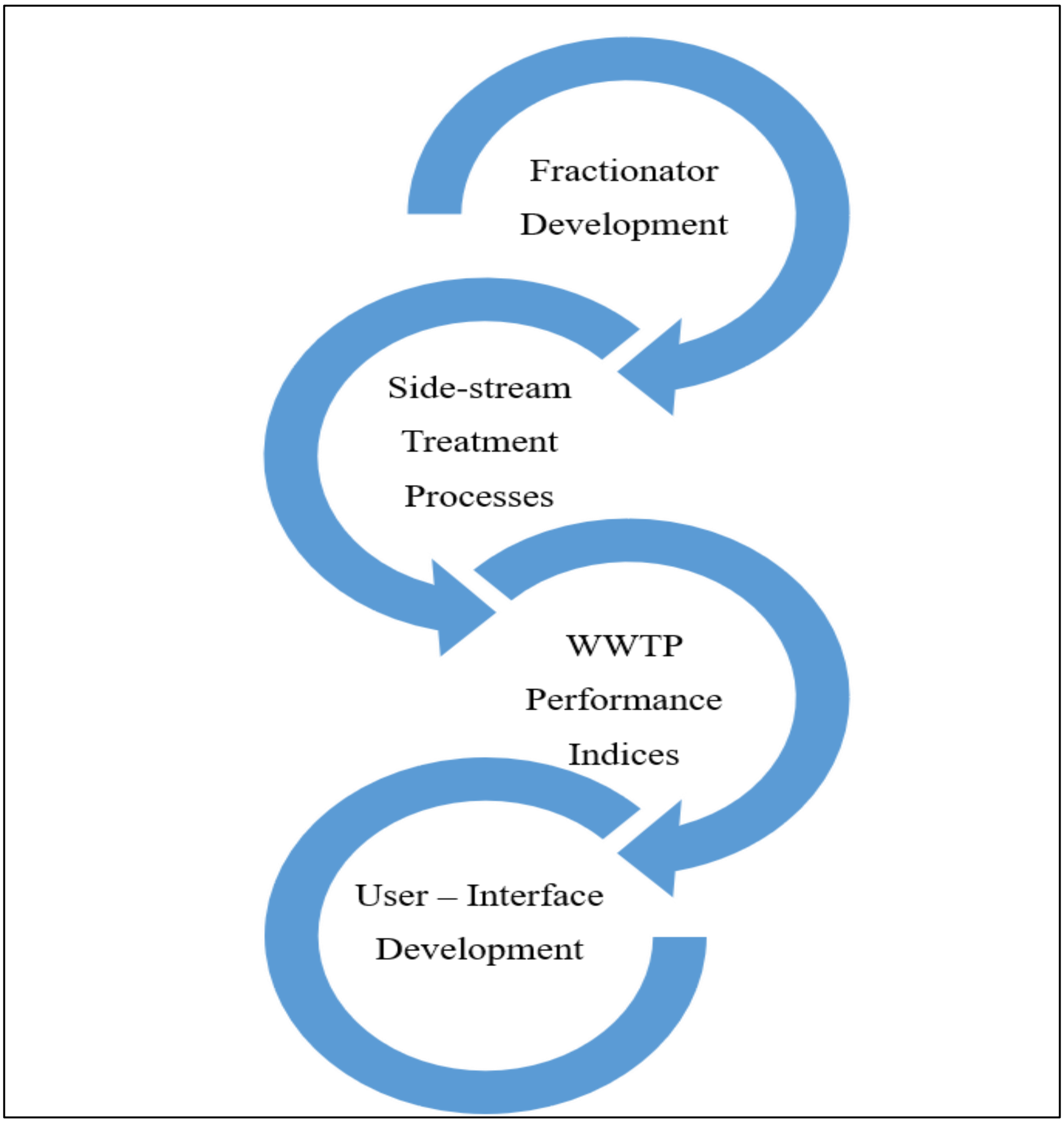

Figure 3-1: Summary of the tool development process

3.2 Model Simplification

The plant-wide model simplification consisted of several steps described in the following subsections.

3.2.1 Wastewater Fractionator

Influent wastewater fractionation is done primarily to reconcile influent data so that the different wastewater constituents can be identified. Comprehensive and accurate wastewater characterisation is essential to the success in prediction of system performance using models (Section 2.1.4). The fractionator (Brouckaert *et al*., 2016) was developed with the aim of enabling the user to generate influent wastewater values based on previous measurement and knowledge from the research where these measurements are missing. It was developed in Microsoft Excel with integrated platforms, such as capturing measured data, data interpolation, data estimation and fitting process, for recording the measured data and estimating the missing data based on the historical records (refer to Section 5.2.1 for more details).

The developed fractionator uses weighted least-squares optimisation to statically estimate the composition of the influent wastewater constituents. The influent wastewater composition is calculated using an algorithm that estimates the composition based on literature or previous experience and modifies the values where one or two measurements are identified. Table 3-1 captures some of the PWM_SA plant wide model component concentrations were used to calculate the different influent wastewater constituents. Additionally, a solver function is used to ensure that the component concentrations are adjusted as close as possible to the inferred values (equation 3-1). The measured values are given a higher weighting while the estimated values are given a lower one.

$$min \sum_i w_i * [fitted_i - inferred_i]^2 \qquad 3\text{-}1$$

Table 3-1: Model components used in the fractionator

Component	Description	Units	Steady-state model component
s_NH	Ammonia	mg/L NH3	Ammonia
s_VFA	Acetate	mg/L Hac	Acetate
s_PO4	Phosphate	mg/L PO4	Orthophosphate
s_U	Unbiodegradable soluble organics	mg/L S_U	USO
s_F	Biodegradable soluble organics	mg/L S_F	FSO
x_U_Inf	Unbiodegradable particulates organics	mg/L X_U_Inf	UPO
x_OHO	Ordinary heterotrophic organisms	mg/L OHO	Not currently in the influent fractionation of the steady state model
x_B_Inf	Biodegradable particulate organics	mg/L X_B_Inf	BPO
x_ISS	Inorganics suspended solid	mg/L X_ISS	ISS

Lastly, the fractionator uses a correlation (Table 3-2) to estimate the missing measurements based on ratios of other measurements as summarised in equations 3-2 to 3-13.

Table 3-2: Correlation factors used to generate estimates

Parameter	Description	Default values
f_tss	Ratio of TSS to total COD	-
f_codus	¤ Un-biodegradable soluble fraction of total COD	-
f_codup	Un-biodegradable particulate fraction of total COD	-
f_tkn	Ratio of TKN to total COD (mg N/mg COD)	-
f_fsa	Ratio of FSA/TKN (mg N/mg N)	-
f_vfa	Fraction of total COD contributed by VFAs (taken to be acetic acid)	-

Parameter	Description	Default values
f_codf	Soluble fraction of total COD	-
f_tknf	Ratio of filtered TKN to total COD	-
f_tp	Ratio of total phosphorus to total COD (mg P/mg COD)	-
f_tpf	Ratio of filtered total phosphorus to total phosphorus	-
f_iss	Inorganic fraction of total suspended solids	0.1
f_bp_ns	Non-settleable fraction of the biodegradable particulate COD	0.6
f_up_ns	Non-settleable fraction of the unbiodegradable particulate COD	0.4
f_iss_ns	Non-settleable fraction of ISS	0.1
f_setsewflow	Fraction of raw sewage going to settled sewage	0.985
f_bu	Ratio of biodegradable to unbiodegradable particulate COD	4.7

$$f_{\_tss} = \frac{Average\ TSS}{Average\ COD} \qquad \text{3-2}$$

$$f_{\_TKN} = \frac{Average\ TKN}{Average\ COD} \qquad \text{3-3}$$

$$f_{\_fsa} = \frac{Average\ FSA}{Average\ TKN} \qquad \text{3-4}$$

$$f_{\_tp} = \frac{Average\ TP}{Average\ COD} \qquad \text{3-5}$$

$$f_{\_tpf} = \frac{Average\ OrthoP}{Average\ TP} \qquad \text{3-6}$$

$$f_{\_codus} = \frac{Average\ COD\_us}{Average\ COD} \qquad \text{3-7}$$

$$f_{\_tss} = \frac{Average\ TSS}{Average\ COD} \qquad \text{3-8}$$

$$f_{\_iss} = \frac{Average\ Settlable\ IS}{Average\ TSS * (1 - f_{iss_{ns}})} \qquad 3\text{-}9$$

$$f_{\_iss} = \frac{Average\ Settlable\ IS}{Average\ TSS * (1 - f_{iss_{ns}})} \qquad 3\text{-}10$$

$$f_{\_setsewflow} = \frac{Average\ Flow\_setsew}{Average\ Inflow} \qquad 3\text{-}11$$

$$f_{codup} = (1 - f\_iss)\frac{f\_tss}{\left(\frac{1}{X\_U\_COD} + \frac{f\_bu}{X\_B\_COD}\right)} \qquad 3\text{-}12$$

$$f_{codf} = 1 - (1 + f_{bu})f\_codup \qquad 3\text{-}13$$

3.2.2 Simplified Steady State Model

There have been several developments of complex single unit process steady-state models. Table 3-3 summarises different components of the model that were incorporated in the tool. These models aim to replicate biological processes taking place in WWTPs. The various previously developed single unit process models relevant to this project, namely, influent wastewater characterisation, activated sludge reactor (i.e., organism growth and decline, nitrification-denitrification models and biological excess phosphorus removal models), anaerobic digestion of primary and secondary sludge, were linked together to form a plant-wide model such that the outputs from upstream unit process become outputs for the downstream unit process. The plant-wide steady-state model was formed based on the principles of material (carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and phosphorus (P)) mass and charge balanced bioprocess stoichiometry and assigning elemental compositions to all the organic components (i.e., $C_xH_yO_zN_aP_b$ – this enables linking the activated sludge model of Wentzel *et al.* (2008) with the anaerobic digestion (AD) model of Sötemann *et al*. (2005)) so that these and their products can be traced throughout the WWTP (Ekama, 2009). The steady-state plant-wide model was developed in Microsoft Excel (refer to Section 2.3).

Table 3-3: Summary of WRRF models incorporated in the developed tool

Process model	**Reference**
Activated sludge steady-state behaviour	Marais and Ekama, 1976
Organic material removal	Ekama and Wentzel, 2008a
Biological nitrogen removal	Ekama and Wentzel, 2008b
Nitrification denitrification enhanced biological phosphorus removal	Wentzel et., 2008
Anaerobic Digestion	Sötemann *et al*., 2005
Plant-wide mass balance steady state WWTP model	Ekama, 2009

3.2.3 User-interface

A suitable user-friendly interface for the simplified steady-state plant evaluation tool was developed with the intent of bridging the gap in knowledge between modellers and stakeholders. This interface was developed in Microsoft Excel visual basic for applications (VBA) coding. Menniti *et al*. (2018) recommends that to overcome the challenge of complex model simplification and to increase its uptake by stakeholders, the modeller should work closely with the involved stakeholders and the level of accuracy of the outcomes from the model should be made clear in the developmental stage of the model. Furthermore, stakeholders should be trained on how to use the developed simulation model if necessary. The user-friendly interface development process consisted of two stages. The first stage was about gathering information about why the tool would be useful and what information is expected to be generated from the tool. This information was gathered from stakeholders through means of a questionnaire and interviews (Appendix A and Appendix B). This questionnaire was completed by several stakeholders who were selected to be involved in the tool development process. The stakeholder selection process was based on the level of the knowledge of the stakeholder i.e., varying from those with a background in mathematical modelling to those with no modelling background so that the final tool developed can be used by stakeholders of varying modelling experience (see Section 4.2 for a summary on questionnaire results). Finally, the last stage was the development of a user-friendly interface in consultation with the stakeholders since they are the most likely users of the tool (Section 4). This stage involved several iterations of the interface development until the final suitable interface was selected.

3.2.4 Model Implementation

To generate confidence in the model prediction outputs, four steps were used. The first step is the validation of the fractionator. This step entails evaluating whether the predicted outputs fall within acceptable ranges for the historical data for the plant. The second step is a fractionator evaluation which involves analysing the most important measurements that affect the accuracy of the fractionator outputs. This analysis was carried out by randomly running the steady-state fractionator with varying measurements namely, chemical oxygen demand (COD), total kjeldahl nitrogen (TKN) and total phosphorus (TP), to examine which of these measurements has the biggest impact on the results (Section 5.2.2). The third step is the calculation of material mass balances over unit processes. To ensure that the developed mathematical steady-state model is scientifically sound, material and energy balances were checked over the various unit processes to affirm the conservation of mass and charge. The last step is qualitative observation, narrow-based model calibration, against selected full-scale systems.

3.2.5 Side-stream Treatment Process models

The mitigation measures for ensuring that there is a lowered negative impact on the full-scale plant performance due to recycling dewatering liquors were considered. Several side-stream technologies are available and are worldwide recognised as efficient to reduce nitrogen (N) and phosphorus (P) concentrations in the sludge return liquors. Most applicable technologies for side-stream N removal are based on ammonia oxidation over nitrite and/or nitrogen gas and occurring at high process temperatures (30 to 40°C). These solutions are marketed as SHARON® and ANNAMOX® and claim high levels of efficiency (van Loosdrecht and Salem, 2006). However, the bottleneck of these solutions is usually the high investment cost and high level of complexity and maintenance requirements. On the contrary, bio-augmentation batch enhanced (BABE) process appears to be a low-cost method for N removal, simple operation allowing for an improved nitrification process in the main plant due to the recycling of nitrifiers from the side-stream treatment. Due to these characteristics and assuming the South African challenges in terms of capital investment and maintenance requirements, it looks like the BABE technology may have an advantage compared to other more complex options.

Table 3-4: Decision matrix for selection of a sludge treatment process in 's-Hertogenbosch WWTW in the Netherlands (adapted from Berends et al., 2005 a)

Aspect	SHARON	SHARON/ANAMMOX	CANON	BABE
Investment cost	+	0	++	+
Operational cost	++	++	++	++
Allowable increase of load	–	–	–	+
Impact on final effluent	–	–	–	+
Sustainability	0	+	+	0
Ease of retrofitting	+	+	+	0

Notes:++ = 5; + = 4; 0 = 3; – = 2; – – = 1

Berends et al. (2005a) developed a decision-making matrix that is used to weight various N removal side stream technologies. This decision matrix was used to show that BABE process is the best technology for N removal compared to SHARON, ANAMMOX and Canon for ‘s-Hertogenbosch WWTW. For the objective of this research, i.e., to evaluate the impact of side stream treatment technologies on overall plant performance, BABE process was recommended as the primary technology to be incorporated in the tool to be developed. This process offers higher benefits in key decision/priority areas which are OPEX, future load increase and impact on final effluent, as well as indicates considerable benefits in terms of investment costs. However, it should be noted that future developments of the tool should incorporate other N removal side stream technologies so that different benefits of each technology, specifically for South African WWTPs, can be evaluated.

In terms of P removal solutions for SSTPs, there is also a wide variety of options available, from conventional coagulation, flocculation and sedimentation using metal-salts for chemical P precipitation, up to more complex processes with chemical crystallization in up-flow fluidized bed reactors with dosages of calcium or magnesium in controlled pH conditions allowing for a high-phosphate recovery in the form of struvite. Examples of these technologies are marketed as Ostara Pearl®, WASSTRIP®, AIRPREX®, Crystalator®, Calprex™, Phospat™ amongst others. These technologies provide a wide variety of struvite quality which ranges from low to premium grade. Presently the South African market value for struvite recovery and application is not cost-effective compared with the conventional chemical precipitation solutions (Sikosana *et al*., 2014). However, it is important to keep in mind the potential environmental and economic benefits and the application of sub-products, such as struvite, in agriculture/fertilizers and animal food industries as well as construction materials. South Africa still needs to develop regulations for P recovery and reuse, build governance structures for phosphorous management, encourage trade and use of wastewater sub-products.

Based on the discussion above and for the purpose of this research (Section1.5.3), only BABE and struvite precipitation processes were considered to be the most applicable SSTPs for South African plants. However, the tool was developed in such way that other SSTPs can be incorporated in future versions of the tool.

3.2.5.1 BABE Process

The BABE process that was used in this research project has been briefly discussed to meet the aim of the tool development. Further details about this process are being investigated in a separate study. This process is a new low-cost method for N removal in wastewater treatment (Salem *et al.*, 2003). It allows for the removal of ammonia and the improvement of nitrifiers that are returned to the reactor via the recycle. The process consists of combining the sludge dewatering liquor with a fraction of the return activated sludge (AS) from the biological nutrient removal (BNR) reactor into a nitrifying batch reactor with a short retention time (Figure 3-2). To include denitrification, an anoxic tank is added to the process.

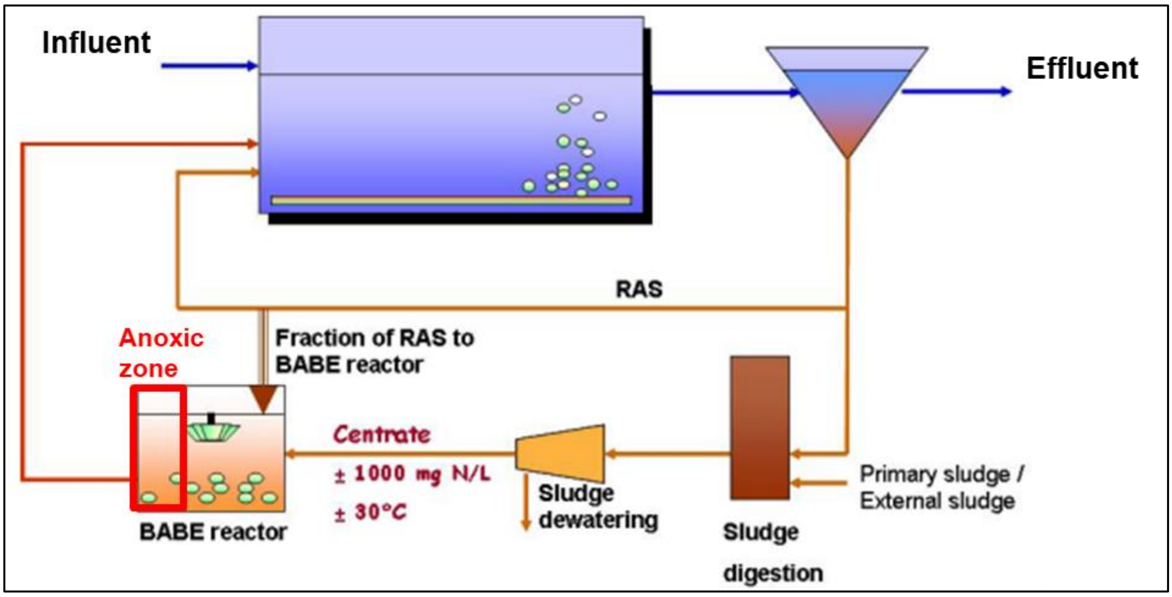

Figure 3-2: BABE process (adapted from Hommel *et al*., 2006)

With the implementation of the BABE SSTP, the introduction of a new term in the nitrification mass balance equation is required (Equation 3-14). This term is known as the specific addition rate of nitrifiers (k_{add}). It accounts for the nitrifiers grown in the side-stream reactor that are recycled back to the mainstream reactor. The specific addition rate of nitrifiers, k_{add}, is calculated as the ratio of the concentration of nitrifiers grown to the total concentration of nitrifiers (Salem *et al*., 2003).

$$\frac{dC_A}{dt} = growth - decay - wasting + addition \qquad 3\text{-}14$$

Equation 3-14 shows the mass balance equation for the population of nitrifiers in the mainstream reactor, with the term "addition" referring to the specific growth rate (k_{add}). The expressions for determining the minimum aerobic sludge age required for nitrification to take place for steady state conditions due to the specific growth rate of additional nitrifiers is expressed as shown in Equation 3-15:

$$SRT^{min} = C_N + K_N C_N \mu^{max} - (k_D - k_{add})\,(C_N + K_N) \qquad 3\text{-}15$$

Where: SRT^{min} = minimum sludge retention time (day); C_N = concentration of the substrate, NH4-N (g/m^3); K_N = half-rate constant for nitrifiers (g/m^3); μ^{max} = maximum specific growth rate of nitrifiers (/day); k_D = endogenous decay coefficient of autotrophs (/day) and k_{add} = specific addition rate (/day)

3.2.5.2 Struvite Precipitation

Struvite ($MgNH_4PO_4.6H_2O$), is a phosphate mineral that is known to precipitate during the anaerobic digestion of sludge in the presence of magnesium ions (Ikumi and Ekama, 2019). Controlled struvite precipitation in the SSTP, containing high concentrations of ammonium and phosphates, helps to reduce the nutrient load on the BNR reactor. Additionally, struvite crystals that precipitated can potentially be used as inorganic fertiliser (Nieminen, 2010). The struvite precipitation process that incorporated in the simplified steady-state tool (PPET) is much simplified and aims at predicting the potential of precipitation.

$$\begin{aligned} RMg^{2+} + RNH_4{}^{+} + 6H_2O + \big((1-f).R\big)HPO_4{}^{2-} + \big((1-f).R\big)HCO_3{}^{-} + \big((1-f).R\big)H_2PO_4{}^{-} \\ \rightarrow 6MgNH_4PO_4 \cdot 6H_2O + \big((1+f)\cdot R\big)H_2CO_3 \end{aligned} \tag{3-16}$$

Mineral precipitation occurs provided that the ionic product of magnesium, ammonia and phosphate exceeds the thermodynamic solubility of struvite (Loewenthal *et al*., 1994). By maintaining pH at 7 and dosing magnesium (if required), struvite precipitates as shown in Equation 3-16. With the number of moles of struvite (R) precipitated calculated, the effluent ammonia and ortho-phosphates can be determined.

The developed tool analyses the impact of recycling DWL to the overall plant performance by checking how treating a percentage of DWL (i.e., from 0% to 100%, the former implying recycling the DWL without undergoing further SSTP while the latter implies that all the DWL is treated) affects the effluent quality and operational cost.

3.2.6 Performance Indices

The incorporation of SSTPs affects WWTP performance. WWTP performance indices are a means of evaluating design/control strategies implemented at WWTP. The performance indices incorporated in the tool are the effluent quality and operational cost indices, EQI and OCI, respectively. These indices are dependent on the limited predictions of steady-state plant-wide modelling and therefore should only be used as an estimate.

3.2.6.1 Effluent Quality Index

The EQI standardises the pollutants discharged by applying weighting factors to each pollutant based on their relative environmental impact. The result is the number of pollutants (in terms of kg) discharged per day. The EQI formulation provided by De Ketele *et al*. (2018) based on the previous work by the International Water Association (IWA) Benchmark Simulation Modelling (BSM) task group (Jeppsson *et al*., 2007) is shown in Equation 3-17. Since the tool is based on a steady-state conditions, the actual calculation is done without time steps.

$$EQI = \frac{1}{T \cdot 1000} \int_{t=0\ days}^{t=365\ days} \big(\beta_{TSS} \cdot TSS(t) + \beta_{COD} \cdot COD(t) + \beta_{FSA} \cdot FSA(t) + \beta_{NO} \cdot NO(t) + \beta_{OP} \cdot OP(t)\big) \cdot Q_e(t) \cdot dt \qquad 3\text{-}17$$

The β factors for each pollutant in the EQI calculation are shown in Table 3-5. These factors are directly related to the effluent concentration limits (e.g. $\beta_{FSA} = \frac{COD\ conc}{FSA\ conc} = \frac{30}{1} = 30$). The β factors give an indication of how harmful pollutants are relative to COD; the larger the β factor, the more harmful the pollutant is.

Table 3-5: Beta weighting factors (De Ketele *et al*., 2018)

Pollutant	Concentration limit (mg/l)	Default β-factor
COD	30.00	1
FSA	2.00	15
OP	1.50	20
NO	2.50	12
TSS	30.00	1

3.2.6.2 Operational Cost Index

The OCI is a measure of the operational cost of implementing design/control strategies at WWTPs. It is formulated as shown in Equation 3-18. For the purposes of this tool, the OCI is limited to energy costs, more specifically aeration energy and methane production.

$$OCI = (AE + PE - MP + ME + HE) \cdot Energy\ cost + SP \cdot Sludge\ disposal\ cost + EC \cdot Carbon\ cost \qquad \text{3-18}$$

Where AE = aeration energy (kWh/d); PE = pumping energy (kWh/d); SP = sludge produced (kgTSS/d); EC = external carbon addition (kgCOD/d); ME = mixing energy (kWh/d); MP = energy from methane produced (kWh/d); and HE = total heat energy required in the anaerobic digester for sludge treatment (kWh/d).

3.3 Steady-State Model Comparison

In order to build confidence in the simplified steady-state model, the results generated by the developed plant-wide model were compared to those of Ekama (2009). The main results that were compared are the influent wastewater characterisation (i.e., probabilistic fractionator outputs comparison, Section 5.2.2), biological nutrient removal processes and the anaerobic digestion outputs.

3.4 South African Case Studies

3.4.1 Background

The developed steady-state simulation tool was used to conduct case studies on three different South African WWTPs (which were part of six pre-selected plants that represented typical South African plants. The aim of the case studies was to evaluate whether there would be an added benefit of incorporating SSTP in WWTPs and to determine the most suitable process.

3.4.2 Descriptions of Systems

The three different WWTPs that were used for the case studies are Plant A (a University of Cape Town, UCT layout), Plant B (a 3- Stage Phoredox layout) and Plant C (a JHB layout) (Wentzel *et al*., 2008). Figure 3-3 is the simplified version of the WWTP layout showing the unit processes that were included in the developed tool because they are relevant to the research project (i.e., examining the impact of sludge dewatering liquors on the overall performance of a WWTP).

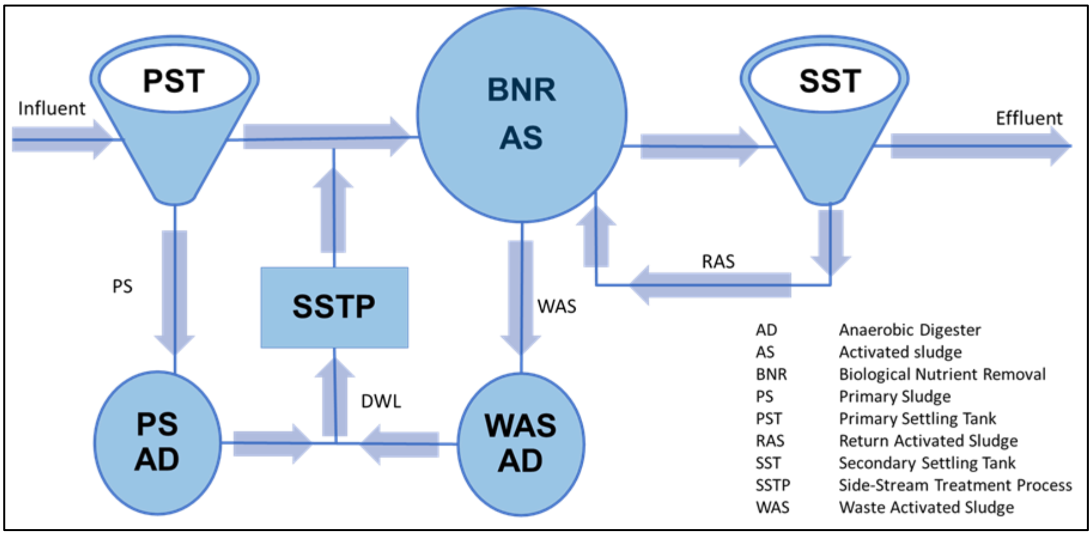

Figure 3-3: Simplified WTTP layout for plants A, B and C

- Plant A consists of four modules each having a capacity of 40 Ml/d besides module 4 which has a capacity of 50 Ml/d. The primary sludge and waste activated, produced in the four modules, is fed into one anaerobic digester of 12 Ml; 50% of the produced DWL is recycled back to modules 1 – 3 while the remaining 50% goes to module 4.

- Plant B consists of two modules, former having a capacity of 45 Ml/d and the latter 40 Ml/d. The PS and WAS produced from each module are sent into separate anaerobic digesters. The resulting DWL is treated into two precipitation tanks where the lime slurry is dosed to increase the pH and precipitate orthophosphate. These tanks are also designed to strip ammonia. The treated DWL is recycled back at the beginning of module 2.
- Plant C consists of one module, a JHB BNR AS system with a capacity of 9 ML/d. The WAS is anaerobically digested and the resulting DWL recycled back to the mainstream process.

The WWTP information from each of the selected plants (i.e., influent wastewater characteristics, BNR AS configuration, operation and design parameters) were used as inputs for the SS simulation tool. The most important unit operations that were selected with respect to this study are primary settling tank, BNR AS system and anaerobic digestion. Since the developed tool is limited to analysing only one module, the information for module one of each of the selected plant was used. Table 3-6 and Table 3-7 summarise the general characteristics and unit processes/operations and the input parameters for the selected plants.

Table 3-6: WWTP unit operations and processes for plant A, B and C

Key Unit Operations and Processes	**Sizes**	**Module 1**			**Module 2 & 3**		**Module 4**
Plant	-	Plant A	Plant B	Plant C	Plant A	Plant B1	Plant A
Primary Settling Tanks	Diameter (m)	25	4×22	25	25	3×25	34

[1] Please note that plant B has only two modules.

Key Unit Operations and Processes	Sizes	Module 1			Module 2 & 3		Module 4
BNR System	Volume (m^3)	5940	2×19575	5940	15898 each	2×19575	21688
Secondary Settling Tanks	Diameter	30	4×32	30	25	4×35	34
Anaerobic Digesters	Volume (m^3)	–[2]	2×6000	424	–	2×5380	–
Module Capacity	Ml/d	40	45	9	40	40	50

Table 3-7: General input parameters

Parameter	Value at 20 ºC	Unit
Design Sludge Age, SRT	10	d
Factor of safety	1.25	Constant
Number of Anaerobic Reactors in Series	2	–
Population	5000	–
Energy cost	62.03	c/kWh
System Temperature	18	°C
Aeration power	1.2	kgO_2/kWh
Diluted Sludge Volume Index	160	mL/g
Peak factor (PWWF/ADWF)	2.0	–

[2] For Plant A, all modules feed PS and WAS into an anaerobic digester of 12 Ml.

Influent wastewater measurements were used in the fractionation tool to generate influent wastewater characteristics. The outputs from the fractionator were then used as inputs into the developed simplified steady-state simulation tool based on the configuration of the selected plant to determine the effluent concentration and examine the impact of DWL on the performance of the plant.

3.5 Closure

The simplified full-scale steady-state simulation tool was developed in such a way that the input information of the selected system (i.e., influent wastewater characteristics, types of BNR AS configurations, operation and design parameters) directly resulted in the model tailoring to virtually replicate the relevant system processes. The simplification of the complex WWTP models into user-friendly WRRF evaluation tools incorporated the development of a fractionator that reconciles influent wastewater measurements; comparing the WRRF models with sound validated models; developing a user-friendly interface in collaboration with stakeholders and then, comparing the results of this tool with results from the steady state model of Ekama (2009). The SSTPs, namely, BABE process and struvite precipitation; and the plant performance evaluation i.e., EQI and OCI, were developed in a separate study. However, they were incorporated into the developed tool.

The developed tool is currently limited to running and analysing only one module at a time and considers only BABE and struvite precipitation SSTPs. Furthermore, this tool uses EQI and OCI to evaluate the performance of South African WWTPs. The DWL recycled back from the thickening units was not considered in the SSTP because they contain an insignificant concentration of N and P compared to the DWL recycled from the anaerobic digester. Therefore, different scenarios were evaluated for operating the full-scale system with a percentage of DWL (0% to 100%) being treated before it is recycled back to the mainstream process. With these limitations, there is room for improving this tool such enabling it to analyse more than one module, adding other side stream technologies such as ANNAMOX and SHARON and extending the evaluation framework.

4. Tool Description

4.1 Introduction

This chapter consists of three subsections that briefly describe the simplified steady state full-scale wastewater treatment plant (WWTP) tool that was developed for evaluating the impact of sludge dewatering liquors on the overall plant performance. This tool is hereafter referred to as plant performance evaluation tool (PPET) and the term water and resource recovery facility (WRRF) is used to refer to wastewater treatment plant throughout this chapter. Sections 4.3 and 4.4 discuss the objectives and limitations of the tool, respectively. Lastly, Section 4.5 gives a detailed description of the user-friendly interface which consists of five pages, namely, (i) Home Page, (ii) Input Parameters, (iii) Data Reconciliation, (iv) Plant Configuration, (v) Wastewater Characterisation and Results.

4.2 Questionnaire Results

The user interface of PPET was developed in collaboration with several stakeholders through a number of iterative processes i.e., the user interface was first developed, then a questionnaire to capture the easy of using the tool and the relevancy of the results it generated was sent to the stakeholders. Then, the feedback from the stakeholders was used to fine tune the tool. The overall impression was that the developed tool will be useful in the industry. The feedback from the stakeholders is summarised below:

- All the stakeholders indicated that the tool would be beneficial to their organisation because of the results that it generates and its educational use. It was mentioned that the tool would be useful to process controllers who have limited experience with plant modelling.
- The wastewater characterization would provide knowledge on the composition of the wastewater in each plant.
- It was recommended that effluent quality and operational cost indices, EQI and OCI, respectively, should be used as a benchmark for municipal treatment indicators.
- Other feedback relating to the tool interface and changes in the tool, such as allowing the user to enter the effluent quality standards were incorporated in the final tool.

4.3 Tool Objective

The simplified steady-state full-scale simulation tool (i.e., PPET) was developed based on the methodology discussed Chapter 3. It was developed with the aim of increasing its uptake by stakeholders who have limited knowledge and expertise in the processes happening in complex WRRF models. The objectives of PPET can, therefore, be summarised as:

- To evaluate the impact of return dewatering liquor (DWL) on the overall plant performance, namely, operational cost and effluent quality and provide a recommendation for a suitable side-stream treatment process (SSTP) for best effluent quality and lowered operational costs (only struvite precipitation and bio-augmentation enhanced (BABE) SSTPs have been considered);
- To educate the user about treatment processes and how different decisions affect the overall plant performance;
- To bridge the gap between the modellers and stakeholders who have limited technical expertise; and
- To examine the extent to which complex WRRF models can be simplified into simple simulation tools that generate reliable information.

4.4 Tool Limitation

The plant performance evaluation tool (PPET) was fine tuned for South African WRRF operating conditions. Based on the objectives of PPET, discussed in Section 4.3, its limitations are summarised below:

- PPET is limited only to four different WWTP configurations which are commonly used in South Africa, namely university of Cape Town (UCT), modified Ludzack-Ettinger (MLE), 3 stage Phoredox and Johannesburg (JHB) layouts.
- The anaerobic digestion of waste activated sludge (WAS) and primary sludge (PS) is considered. For improvement towards this limitation, it recommended that a choice to select anoxic-aerobic digestion of WAS should be incorporated in the future versions of this tool. The anaerobic digestion of WAS is not efficient unless phosphorus recovery is a requirement

(Ekama, 2017) and dewatering liquor (DWL) discharged from the anaerobic digester undergoes SSTP before it is recycled to the mainstream process.

- Only two SSTPs specifically, bio-augmentation batch enhanced (BABE) and struvite precipitation processes are considered in this tool. For further development, other SSTPs such as anaerobic ammonium oxidation (ANNAMOX) and SHARON can be added into this tool.
- Only two evaluative indices, namely the effluent quality index (EQI) and operational cost index (OCI), were considered and modified to be applicable to South African WRRF conditions. For improvement, the greenhouse gas indices can be added (factored into the equations) as well. This is important because treatment plant emits a large amount greenhouse gas.
- The tool is only useful for replication of steady state system conditions.

4.5 Interface Explanation

The user interface was developed through collaboration with different stakeholders with the aim of making it simple to use.

4.5.1 Home Page

A simple, easy to follow home page was designed with the aim of briefly introducing PPET (i.e., its objectives and limitation to the user). One of the limitations that are emphasised on this page is the fact that tool requires a computer with fast central processing unit (CPU) for it to run the visual basic for applications (VBA) coding which is encrypted it. Furthermore, a simplified version of a full-scale WRRF layout that was used the development of this tool as shown in Figure 4-1.

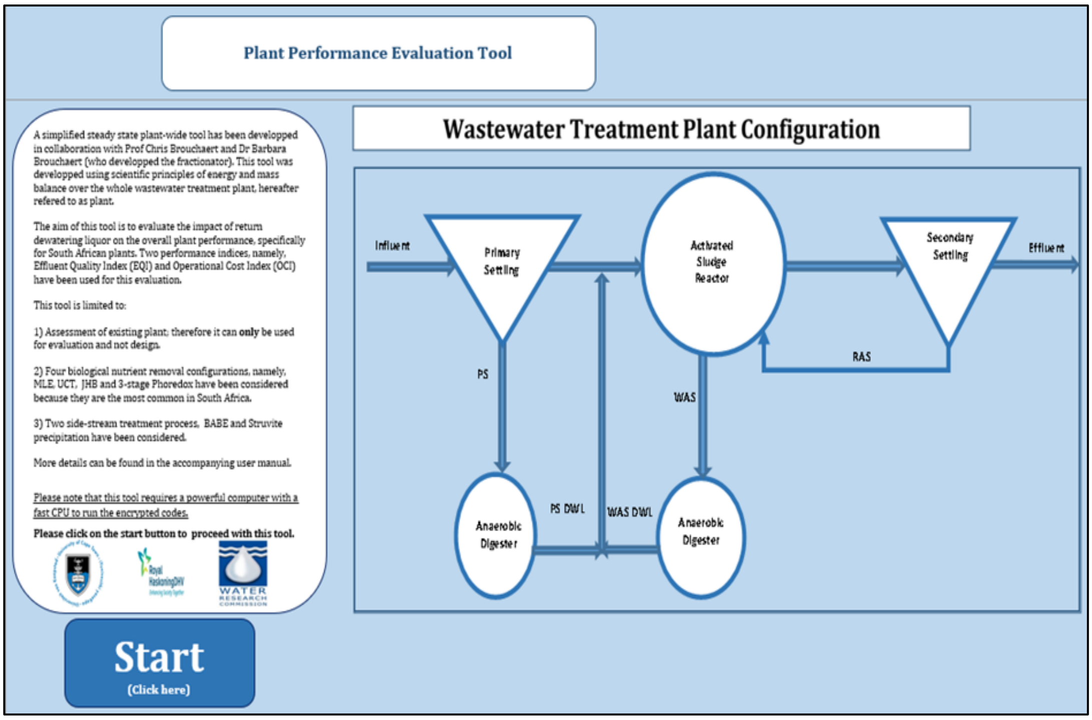

Figure 4-1: Home page of the simulation tool

4.5.2 Input Parameters

This page enables the user to change the state variable design and operation parameters that are needed to run PPET in order to replicate his/her WRRF operating conditions. These inputs parameters have been subdivided into four different categories, specifically, general inputs, biological reactor sizing, anaerobic digestion and effluent quality criteria. Each category is colour-coded to enable the user to link the impact of input parameters to the outputs of the tools summarised in the Results page of the interface (Section 4.5.6). In addition, a user guide has been provided to guide the user in navigating this page (Appendix G).

4.5.2.1 General Inputs

General input parameters such as design sludge age, aeration power, diluted sludge volume index, vary from plant to plant based on the operating condition. Table 4-1 provides a platform for capturing the operational and design parameters for the plant and a recommended range to choose from if the values are not known. The range to choose from was decided based on the typical values that the stakeholders work with.

Table 4-1: General input parameters

General Input					
Parameter	**Abbreviation**	**Value @ 20 °C**		**Range**	**Unit**
		Raw WW	**Settled WW**		
Design Sludge Age, SRT	SRT	10	10	15 to 25	d
factor of safety	Sf	1.25	1.25	1.1 to 1.5	Constant
Number of Anaerobic Reactors in Series	N_{ana}	2	2	-	-
Population	Popn	5000	5000	-	-
Energy cost		62.03	62.03	-	c/kWh
System Temperature	Design Temp	18	18	15 to 25	°C
Aeration power	P_O2	1.2	1.2	-	kgO_2/kWh
Diluted Sludge Volume Index	DSVI	160	160	150 to 250	mL/g
peak factor (PWWF/ADWF)	fq	2.0	2.0	2 to 4	-

4.5.2.2 Biological Reactor Sizing

The biological reactor sizing parameters (Table 4-2) are needed to enable the user to replicate the sizes of the reactors that are being considered. This input section focuses on the actual sizing and fractionation of the flows and mass fractions in the reactor.

Table 4-2: Biological reactor sizing parameters

Biological Reactor Sizing Parameters					
Parameter	**Abbreviation**	**Input**		**Range**	**Unit**
		Raw WW	**Settled WW**		
Total Vol. (VAS)	V_AS	5940	5940	-	m^3
Aerobic Reactor Concentration	Xt	4800	4800	-	mgTSS/l
Aerobic fract.	f_Xaer	0.43	0.43	0 to 1	-
Anoxic fract.	f_Xd	0.4	0.4	0 to 1	-
Anaerobic fract.	f_Xana	0.17	0.17	0 to 1	-
SST Area	AST	1414	1414	-	m^2
anoxic to anaerobic recycle ratio	r_recy	1.00	1.00	0.5 to 5	:1 w.r.t influent flow
mixed liquor recylce ratio	a_recy	4.00	4.00	1 to 10	:1 w.r.t influent flow
Sludge underflow recylce ratio	S_recy	1.00	1.00	1 to 11	:1 w.r.t influent flow
Fraction of influent flowrate (Qi) to Module 1	f_Qi_Mod 1	0.4	0.4	0 to 1	-

4.5.2.3 Anaerobic Digestion

The primary and waste activated sludge, PS and WAS, respectively, are treated in the anaerobic digester to reduce the fraction of active biodegradable organics in them before disposal. Table 4-3 summarises the most important state variables that are needed to model the anaerobic digestion process.

Table 4-3: Anaerobic digestion inputs

Anaerobic Digestion (AD)					
Parameter	**Abbreviation**	**Input**		**Range**	**Unit**
		Raw WW	**Settled WW**		
Fraction of primary sludge fed to AD	f_QPS_AD	1	1	0 or 1	-
Fraction of secondary waste fed to AD	f_QW_AD	1	1	0 or 1	-
Thickening effect on Primary Sludge (PS)	f_PS	100%	100%	0 to 100	%
Required Sludge Age for Anaerobic Digestion (AD)	Rs_AD_min	60	60	-	Days
Selected Total Suspended Solids (TSS) Concentration	AD_TSS	50000	50000	-	mg/l
pH		8.0	8.0	See Step 3	-
Alkalinity		500	500	See Step 3	mg $CaCO_3$/l
Volatile fatty acids	VFA	0.00	0.00	See Step 3	mg/l

4.5.2.4 Effluent Quality

The effluent quality generated by PPET was compared to the special limit standards as recommended by the department of water affairs (i.e., these recommended values were used as default values). The user has the option of changing the effluent quality limits (Table 4-4) provided that there is special permission to use other values.

Table 4-4: Effluent quality criteria inputs

Effluent Quality Criteria				
Parameter	**Abbreviation**	Special limit	Default	unit
Chemical Oxygen Demand	COD	30	30	mgCOD/l
Free and Saline Ammonia	FSA	2	2	mgN/l
Ortho-Phosphate	OP	2.5	2.5	mgP/l
Nitrates	NO_3	1.5	1.5	mgN/
Total Suspended Solids	TSS	10	10	mgTSS/l

4.5.3 Data Reconciliation

This page serves the role recording and reconciling influent wastewater measurements. The fractionation tool was integrated into the steady state full scale WRRF models together with SSTP technologies to form PPET. The fractionation tool plays the role of reconciling influent wastewater measurement and estimate the missing values based on interpolation and fitting processes (Section 5.2). This section requires adding influent measurements that have been made on a yearly, monthly basis or diurnally (Table 4-5 and Table 4-6). The different influent wastewater measurements have been colour coded so that they are linked to the wastewater characterisation (Section 4.5.5).

Table 4-5: Influent raw wastewater measurements

Influent Raw Measurements										
Time	Flowrate	COD	TKN	TSS	TP	FSA	OrthoP	pH_in	Alk_in	Temperature
Days/hours	m^3/d	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	-		°C
2015/09/16	21800	1326	45.1	441	6.6	29.4	2.8	6.9	291	
2015/09/17	24400	876		90		30.4	3.1	6.8	294	
2015/09/18	23300	722				29.9	2.8	6.9	298	
2015/09/19	22100	1331				26.7	2.7	6.6	285	
2015/09/20	22100	1496		500		27.4	3.7	7	289	
2015/09/21	21800	1237		321		26.8	3	7	291	
2015/09/22	16600	872		488		27.4	3.2		331	
2015/09/23	16400	952		441		31	3.9	7.2	317	
2015/09/24	17900	963		175		27.4	3.6	6.7	312	
2015/09/25	31900	648				34	4.1			
2015/09/26	26800	630				29.1	3.8	6.8	311	
2015/09/27	17600	1057		312		28.8	3	7	288	
2015/09/28	17600	617				30.1	3.5	7	262	
2015/09/29	18900	412		94		28.4	3.1	7	284	
2015/09/30	15100	1521	48.6	450	7.5	21.5	2.2	6.8	298	
2015/10/01	17500	1395		280		36.5	3.1	7	292	
2015/10/02	22900	735		250		26.3	3	6.8	288	
2015/10/03	24300	727		322		26.3	2.4	6.8	266	
2015/10/04	19800	1203		313		27.3	2.9	6.9	276	
2015/10/05	16400	808		275		30.2	3.2	7.1	279	
2015/10/06	18400	529		297		23.3	3.3	6.7	237	

Table 4-6: Influent settled wastewater and effluent wastewater measurements

Influent Settled Measurements											Effluent	
Flow_SetSew	COD SetSew	TKN SetSew	TSS SetSew	TP SetSew	FSA SetSew	OrthoP Set Sew	Flow_PS	PS % TS	PS %VS	PS %IS	Effl COD	Effl TSS
m3/d	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	m3/d	%	%	%	mg/l	mg/l
											28	
											47	
											40	11
											37	
	1106	59	286	2.8	42.1	2.9					33	
											46	24
											38	
											41	
											55	
											10	
											25	
	551	68.5	123	6.4	34.3	3.7					28	
											24	
											10	12
											34	
											31	12
											32	
											37	
	821	54.4	145	6.1	38.5	3.9					24	
											10	

4.5.4 Plant Configuration

This page enables the user to select a WRRF layout from the four most commonly used layouts in South Africa, specifically UCT, JHB, 3 Stage Phoredox and MLE (Figure 4-2). Additionally, the user has an option of either selecting to use raw or settled for the modelling process. These options were provided to enable the user to modify PPET so that it can replicate his/her WRRF layout. Furthermore, the user has a benefit of examining whether there is any added value of having primary sedimentation tank and choosing a particular WRRF configuration for treating the influent wastewater.

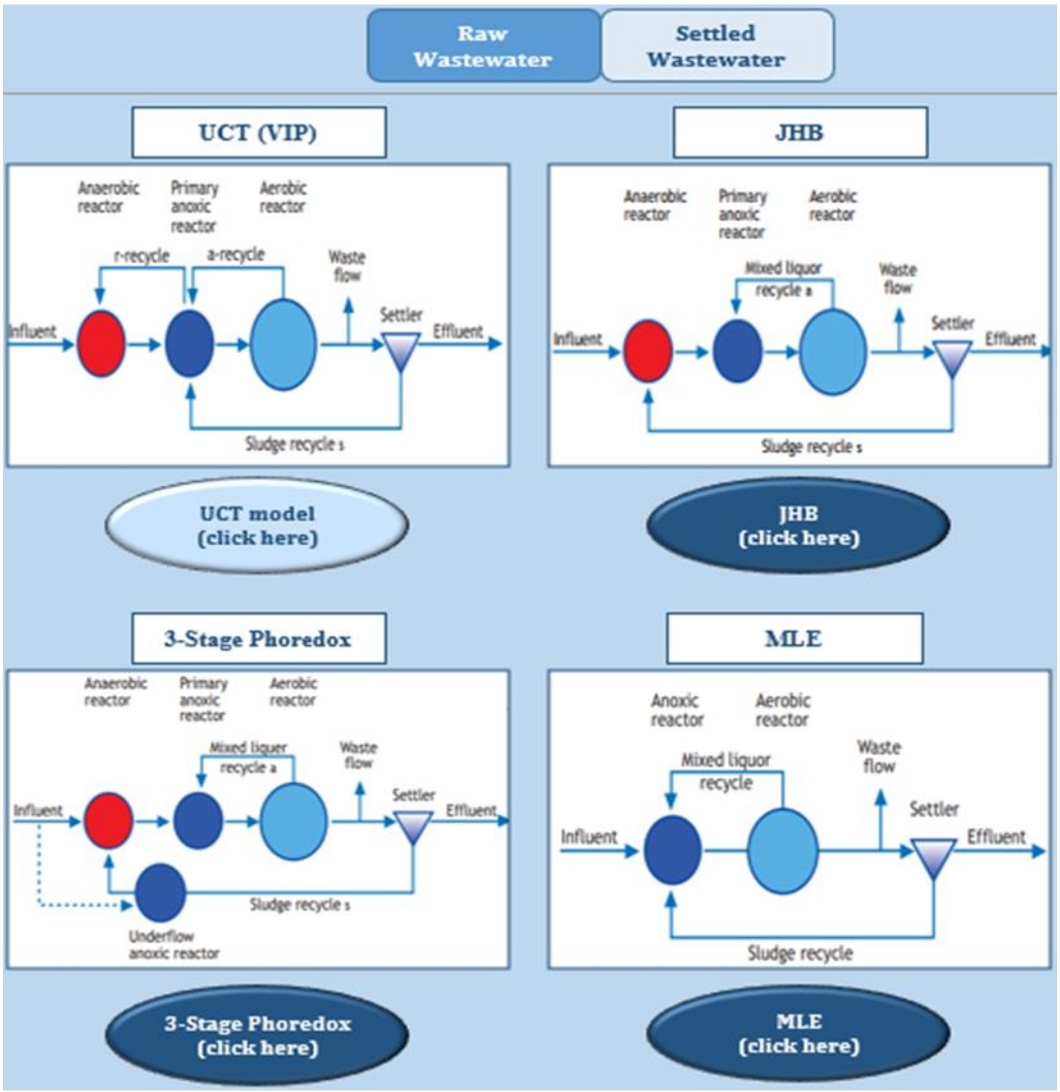

Figure 4-2: Selection of WWTP configuration

4.5.5 Wastewater Characterisation

The main aim of this page is for educational purposes, in other words, to enable the user to connect the link between influent wastewater measurements and the subdivisions of each influent waste characteristic (Figure 4-3). These wastewater characteristics are used as inputs for the biological nutrient removal models.

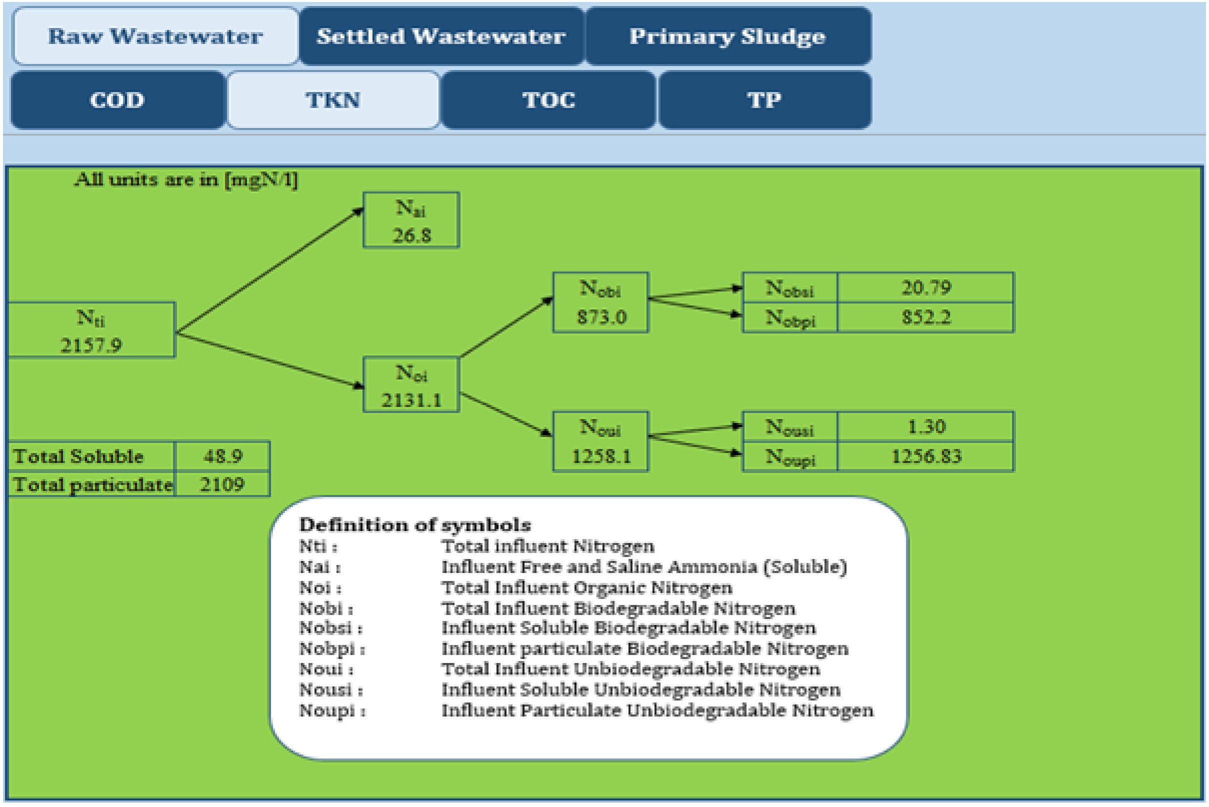

Figure 4-3: Raw wastewater TKN characterisation

4.5.6 Results

This page enables the user to access result from PPET based on the input parameters, influent wastewater characteristics and WRRF layout. The most important results, according to the information gathered from the stakeholders, are biological reactor outputs, anaerobic digester dewatering liquor composition and the effluent quality. The plant performance and recommendation for the most suitable SSTP are also summarised in this page. Figure 4-4 shows the results' interface once the JHB model has completed running. To view, any of the results click on the buttons.

Figure 4-4: Interface for the results section

For example, by clicking on the Biological Reactor button the results will be displayed as shown in Table 4-7, and the results will be displayed.

Table 4-7: Biological reactor results

Parameter	Units	No side-stream treatment	Struvite precipitation	BABE process
Minimum sludge age for nitrification	days	8.35	8.35	8.35
Optimum a- recycle ratio	ratio	10.00	10.00	10.00
Carbonaceous Oxygen demand	KgO/d	4244	4244	4244
Nitrification oxygen demand	KgO/d	651	608	486
Peak oxygen demand	KgO/d	4487	4471	4425
Aeration Power Requirements	kW	224	224	221
Secondary Sludge produced	kgTSS/d	2882	2820	2882
PolyP produced in WAS (excess P removal)		35	16	34.86

4.6 Closure

One of the objectives of this project was to develop a user-friendly interface to increase the uptake of using WWTP modelling tools by various stakeholders. This interface was successfully developed in collaboration with stakeholders. It consists of five pages, namely, Home Page, Input Parameters, Data Reconciliation, Plant Configuration, Wastewater Characterisation and Results. These pages enable the user to (i) capture data for his/her plant of interest; (ii) track materials (C,H,O,N,P) through the plant to predict products generated, hence the plant performance and effluent quality; (iii) evaluate the impact of sludge dewatering liquors on the overall plant performance; and (iv) find the most suitable SSTP.

5. Tool Evaluation

5.1 Introduction

This chapter consists of two main sections in which the methods that were used in evaluating the accuracy of the results generated from the tool are briefly discussed. Section 5.2 discusses the fractionator evaluation which was accomplished through an inbuilt fractionator validation check and by comparing its outcome with the Ekama (2009) steady state model. Section 5.3 discusses the steady state model evaluation, by tracking full-scale mass balance over the full-scale wastewater treatment plant (WTTP) and by comparing the results generated from the tool with plant wide steady-state model of Ekama (2009) results. The term water and resource recovery facility (WRRF) is used refer to wastewater treatment plant (WWTP). Furthermore, the term tool refers to the developed simplified steady state full-scale WWTP evaluative tool. This term is also used interchangeably with the term PPET (plant performance evaluation tool).

5.2 Fractionator Evaluation

5.2.1 Fractionator Validation

The fractionator (Section 3.2.1) was first validated by noting whether it qualitatively predicted the outputs within acceptable ranges of the influent measured data. This was accomplished through comparing the measured data with the estimated and fitted values. Figure 5-1 to Figure 5-4 compare the influent raw organics, expressed in terms of chemical oxygen demand (COD), total suspended solids (TSS), total Kjeldahl nitrogen (TKN) and total phosphorus (TP) measurements with their respective interpolated and fitted values for plant A, a South African WRRF that was used in to conduct case studies (Section 3.4). Refer to Table A-1 (Appendix A) for the measured, estimated and fitted values.

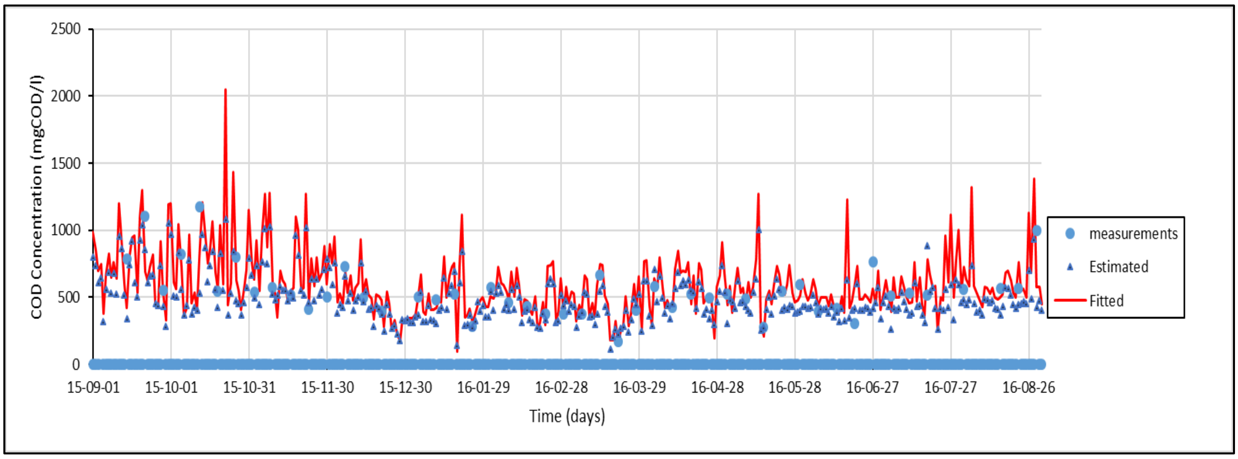

Figure 5-1: Comparison between measured, estimated and fitted COD values

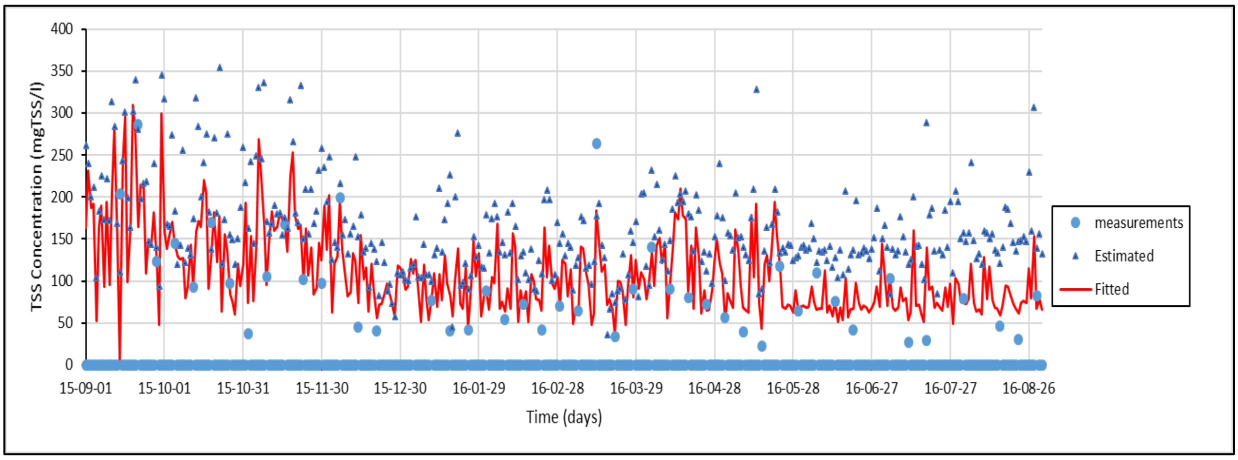

Figure 5-2: Comparison between measured, estimated and fitted TSS values

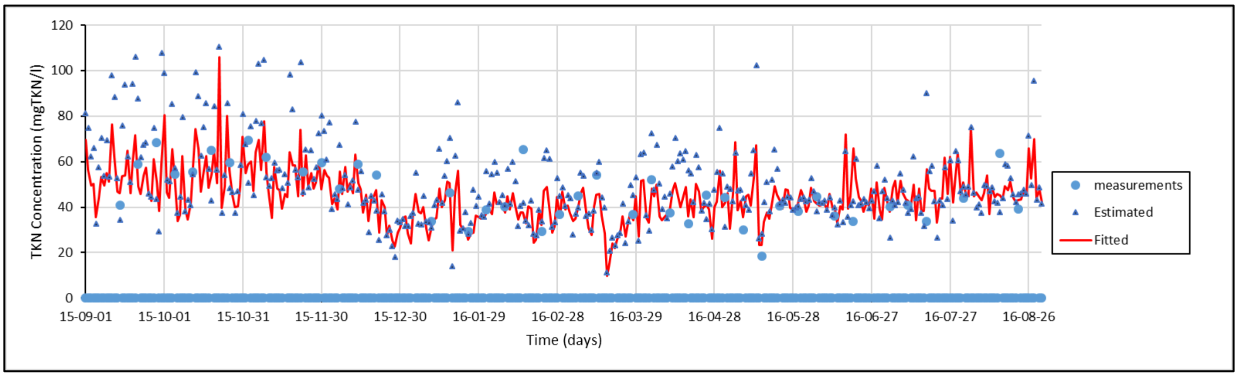

Figure 5-3: Comparison between measured, estimated and fitted TKN values

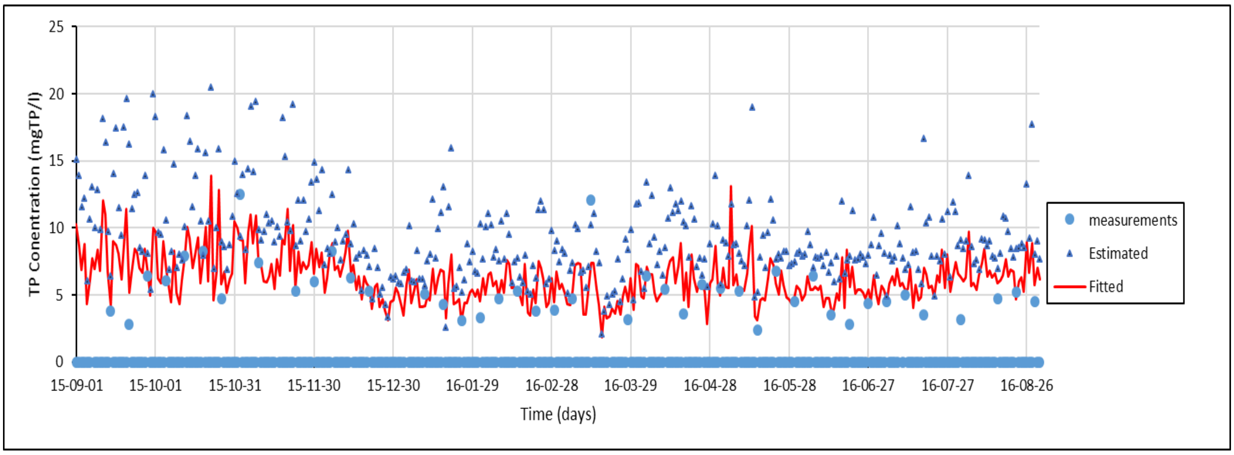

Figure 5-4: Comparison between measured, estimated and fitted TP values

The estimated values in the fractionator are calculated using an interpolation macro coded in visual basics for applications (VBA). This macro estimates the missing data based on (i) the available measurements; and (ii) different fractions of the wastewater constituents which were calculated based on historic influent WRRF measurements or literature if they have not been recorded (Ekama, 2017 and WRC, 1984; Section 2.1.4). The interpolation macro also generates weights for each variable which are then used in the fitting procedure based on the type of measurement and whether there is an actual measurement or just an estimate. The fitting macro, coded in VBA, is used to calculate the fitted measurements by finding the values which best fits the inferred measurements (i.e., the actual measured or estimated values) using weighted least squares. The richer influent measurements data (in other words, the fewer the missing values), the more accurate the fractionator outputs i.e., the closer the measured, estimated and fitted results; for instance, the COD results are more accurate because sufficient measurements were taken. On the contrary, the fewer the measurements, the lower the accuracy, for instance, the TKN fit (Figure 5-3).

5.2.2 Fractionator Analysis

The fractionator validation was not found to be a good enough proof to conclude whether the generated results are accurate. Therefore, the second method of fractionator validation i.e., comparing its outputs with those of validated models (Ekama, 2009) was used to examine whether the fractionator does not have an inbuilt error. The aim of this analysis was to evaluate the accuracy of the in-built interpolation and fitting macros (Section 5.2.1). This was accomplished by using the fractionator to run a complete set of influent raw wastewater measurements (i.e., with no missing measured data, Table D- 3 to Table D- 7 of Appendix F) and then compare how the estimated and fitted values from the fractionator compares to the measured values. This comparison consisted of two steps, namely, fine tuning influent wastewater fractions to match the data being used and then using the fractionator to determine the different components of the influent wastewater characteristics. Figure 5-5 to Figure 5-8 show the comparison of the raw wastewater measured, estimated and fitted values for the data of the design project based on the fractionator.

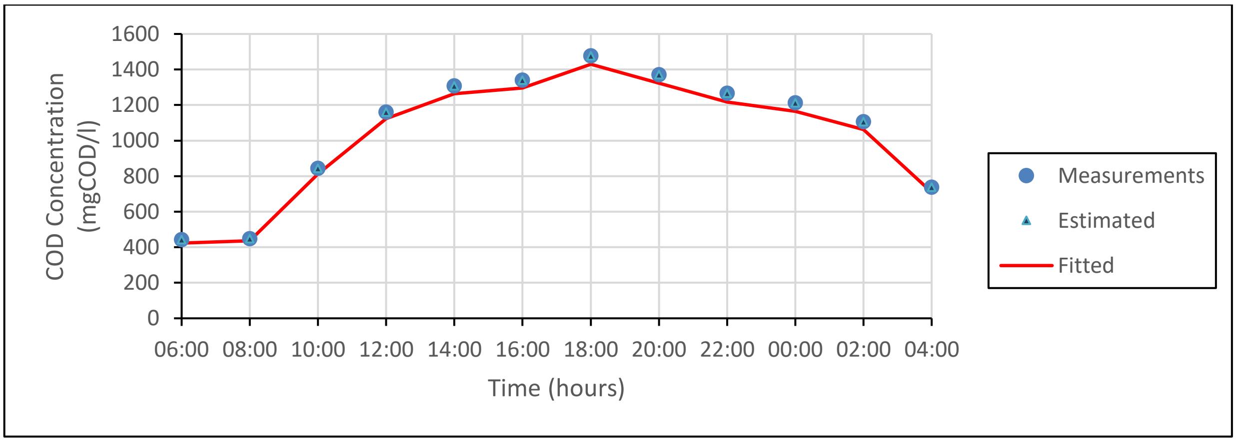

Figure 5-5: COD profile

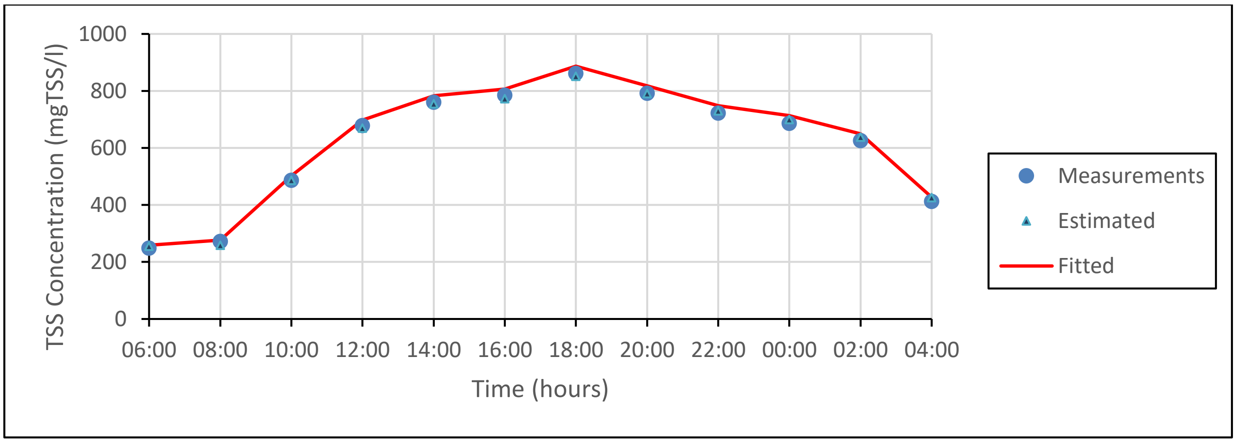

Figure 5-6: TSS profile

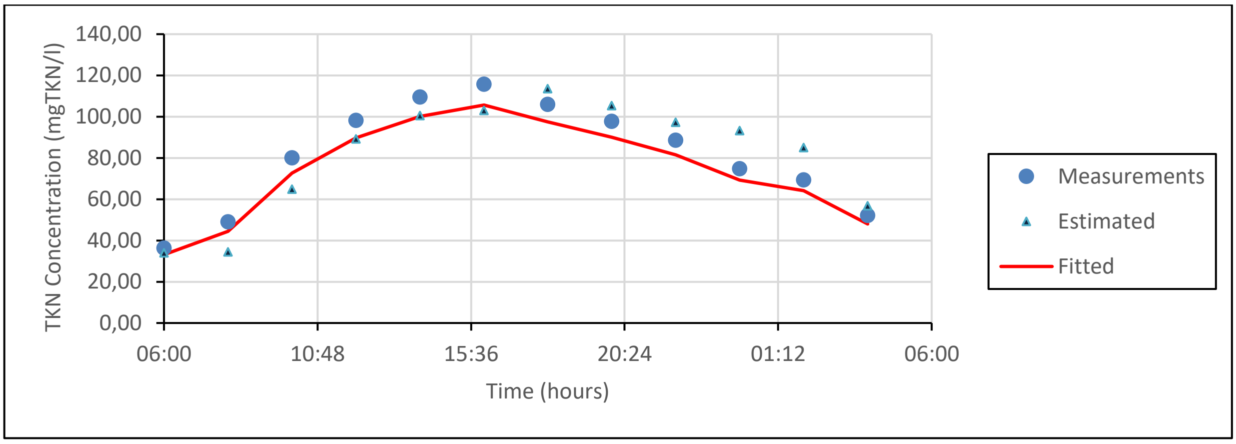

Figure 5-7: TKN profile

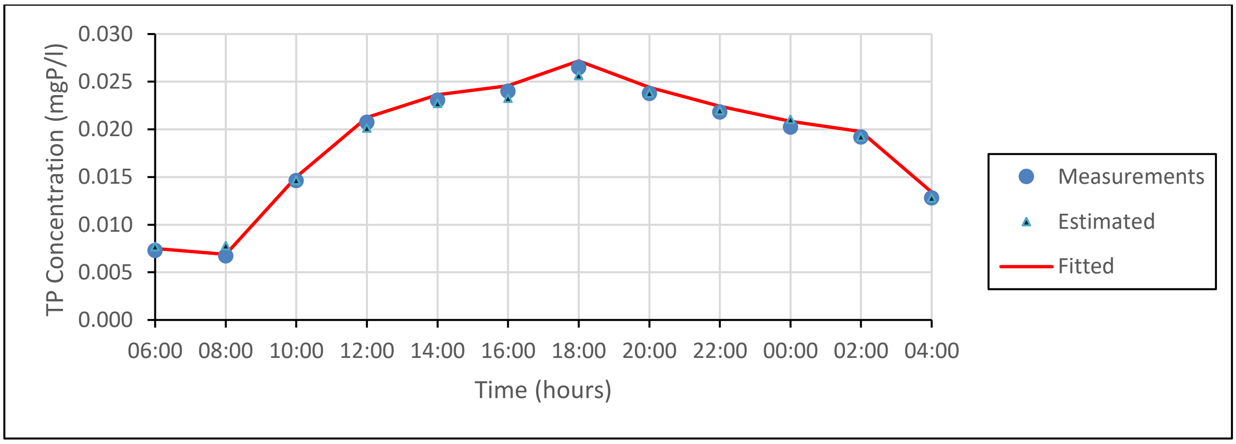

Figure 5-8: TP profile

Based on the fractionator results as summarised in the figures above, the fractionator does not accurately subdivide the different components of the influent wastewater, especially for the TKN fractions. It is assumed that this is due to in-built error in the interpolation and fitting macros. However, this does not imply that the developed tool is not useful. The objective for the tool development was to develop a tool that can always be improved but present a simplified modelling process and bridge the gap between modellers and WRRF stakeholders. Therefore, it is recommended that the fractionator would be developed to accurately characterise influent wastewater. Refer to Appendix F for detailed results comparing the fractionator outputs to those of the Ekama (2009) models for raw, settled and primary sludge influent characteristics.

5.3 Mass Balance

To ensure that the mathematical steady-state models were internally consistent, material and energy balances were checked over the various unit processes to affirm the conservation of mass and charge at 100%. The following tables viz. Table 5-1 to Table 5-4 shows the results of this model verification process.

Table 5-1: COD balance

Constituent	Value	Units
Total influent COD	1786	kgCOD/d
Total effluent COD	2837	kgCOD/d
Total COD of in the waste flow	7089	kgCOD/d
Nitrification oxygen demand	2958	kgCOD/d
Carbonaceous oxygen demand	4502	kgCOD/d
Total COD out	1786	kgCOD/d
COD balance over the plant	100	%

Table 5-2: Nitrogen balance

Constituent	Value	Units
Total Influent Nitrogen	1894	kgN/d
Total nitrogen in the effluent	462.7	kgN/d
Total Nitrogen in the waste flow	485.6	kgN/d
Total nitrogen denitrified in the anoxic zone	945.2	kgN/d
Total nitrogen out	1894	kgN/d
Nitrogen balance over the plant	100.00	%

Table 5-3: Phosphorus balance

Constituent	Value	Units

Total influent phosphorus	525.2	kgP/d
Total phosphorus in the effluent	84.72	kgP/d
Total phosphorus in the waste flow	440.	kgP/d
Total phosphorus exit system	525.2	kgP/d
Phosphorus balance over the plant	100.00	%

Table 5-4: Metal balance

Constituent	Value	Units
Magnesium Removed	81.29	KgMg/d
Magnesium Wasted	81.29	KgMg/d
Mg Balance	100.00	%
Potassium Removed	126.87	KgK/d
Potassium Wasted	126.87	KgK/d
Potassium Balance	100.00	%
Calcium Removed	21.76	KgCa/d
Calcium Wasted	21.76	KgCa/d
Ca Balance	100.00	%

5.4 Closure

The developed simplified plant-wide steady state model, PPET, was evaluated using different methods to build confidence in the results it generates:

(i) The inbuilt fractionator which helps with consolidating influent wastewater data and subdividing them into their different constituents was evaluated firstly by checking its outcomes based on the inbuilt checking method and secondly by comparing its outcomes with those of wastewater characterisation of Ekama (2009). It was found that though the fractionator does not accurately estimate some wastewater characteristics, yet it provides results which are good enough to be used to continue with the objectives of this tool development.

(ii) A full-scale mass, material and energy balances (COD, TKN, TP and metal balances) were checked to affirm the conservation of mass and charge at 100%. Full balances were achieved over the whole plant besides for COD which was at 99.99%.

6. Results and Discussions

6.1 Introduction

This chapter provides brief discussions on the results from the developed plant performance evaluation tool (PPET) using South African case studies. Furthermore, the results from PPET are compared with those predicted using the steady state model of Ekama (2009) with the aim of reconciling the discussions to the objectives of this research project. The objectives of this research project (Section 1.5) can be summarised as: (i) converting complex wastewater treatment plant (WWTP) models into simple evaluative water and resource recovery facility (WRRF) tools that can be used by stakeholders with limited modelling expertise; (ii) compare the results from the developed tool to those of validated simulation model (Ekama, 2009); and (iii) use the developed tool to conduct a case study on South African WWTPs. Section 6.2 discusses the results generated by PPET based on the wastewater information (i.e., influent characteristics and design and operational parameters) of the three plants used in the case studies. The results that were deemed important for the tool development, hence included in the discussions below, are those of biological reactor and anaerobic digestion processes, effluent quality and plant performance evaluation which done using effluent quality and operational cost indices, EQI and OCI, respectively. Furthermore, this section discusses the benefits of incorporating side-stream treatment processes (SSTPs), namely, bio-augmentation batch enhanced (BABE) and struvite precipitation on the overall plant performance. The term WRRF has been used to refer to WWTP. The term PPET (plant performance evaluation tool) is used interchangeably with the term tool to mean the developed simplified steady-state mathematical model.

6.2 South African Case Studies

The impact of return dewatering liquor on the overall plant performance was analysed for three South African wastewater treatment plants A, B and C. Section 6.2.1 discusses the impact of incorporating a SSTP on the minimum sludge age required for nitrification and the overall oxygen demand for the biological nutrient activated sludge reactor. Section 6.2.2 compares the anaerobic digestor outputs, namely, organics expressed in terms of chemical oxygen demand

(COD), free and saline ammonia (FSA) and orthophosphate (OP) for the different STPs. Section 6.2.3 discusses the results for the effluent quality for the different STPs. Section 6.2.4 evaluates the impact of incorporating an STP on the overall plant performance based on effluent quality and operation cost indices, EQI and OCI, respectively. Lastly, Section 6.2.5 provides a recommendation for the best STP to use based on the configuration of the wastewater treatment plant (WWTP).

6.2.1 Biological Nutrient Activated Sludge Reactor

The bio-augmentation batch enhanced (BABE) process results in lowered minimum sludge age required for nitrification process (Table 6-1). The reduction in the sludge age is associated with the fact that the BABE process recycles nitrifiers, produced in the BABE reactor, to the main treatment process. The addition of these nitrifiers in the activated sludge (AS) reactor results in improved nitrification process at a reduced sludge age (Salem *et al*., 2003), thus lower nitrogen (N) content in the effluent. In addition, the peak oxygen demand decreases with the integration of this process into the mainstream WWTP processes.

The recycling of the untreated dewatering liquor (DWL) to the AS system results in increased oxygen demand to cater for nitrification requirements due to high concentration of N load. The use of struvite precipitation as a STP results in lower nitrification oxygen demand in the parent AS system. This is due to some ammonia being used towards struvite ($MgNH_4PO_4.6H_2O$) in the precipitation process. However, ammonia is usually not the limiting component of the precipitation reaction – the precipitation of struvite usually gets limited by the quantity of magnesium present, with the acceptance of pH being maintained at high value of above 7. The BABE process produced the least oxygen demand because it recycles lower N load compared the struvite precipitation process.

Table 6-1: Biological reactor result for plant A for the option of recycling all (i.e., 100%) anaerobic digestion dewatering liquor

	Plant A			Plant B			Plant C		
Parameter	No SSTP	BABE	Struvite	No SSTP	BABE	Struvite	No SSTP	BABE	Struvite
Minimum sludge age for nitrification (days)	8.35	8.24	8.35	8.35	8.26	8.35	4.45	4.40	4.45
Carbonaceous Oxygen demand (kgO/d)	7459	7459	7459	9794	6102	9773	873	866	866
Nitrification oxygen demand (kgO/d)	5361	4832	4812	4347	4126	4162	675	661	671
Peak oxygen demand (kgO/d)	9812	9561	9552	11730	7958	11641	1189	1176	1181

6.2.2 Anaerobic Digestion

During anaerobic digestion (AD) the organically bound N and phosphorus (P) nutrients are released (as ammonia and orthophosphates) in the aqueous phase. The quantities of ammonia and orthophosphate released during AD of waste activated sludge (WAS) are significant due to the high quantities of N and P bound in the active biomass from AS systems. Consequently, the resulting DWL is rich in N and P nutrients; and if this liquor is recycled without undergoing further treatment, the plant would be overloaded with nutrients without enough biodegradable organics to facilitate the process of removing them. The dewatering liquor generated from anaerobic digestion (AD) systems treating primary municipal sludge (PS) usually have significantly less nutrient (nitrogen (N) and phosphorus (P)) content, than those treating waste activated sludge (WAS) due to the low N and P bound in biodegradable particulate organics from the influent waste (i.e., typical biodegradable particulate organic (BPO) PS composition for municipal waste is $CH_{1.6}O_{0.6}N_{0.03}P_{0.01}$; Ekama, 2017)). However, this may vary depending on the source of the waste stream. The activated sludge (AS) system biomass composition has usually higher N and P content than PS i.e., ordinary heterotrophic organisms (OHOs) have an elemental formula of $CH_{1.5}O_{0.4}N_{0.17}P_{0.02}$ and polyphosphate accumulating organisms (PAOs) $CH_{1.5}O_{0.4}N_{0.17}P_{0.02}\cdot Mg_{0.31}K_{0.29}Ca_{0.05}PO_3$ (Ekama, 2017, Ikumi *et al.*, 2015). This allows for higher nutrient content in the dewatering liquor for AD of WAS since the digestion of activated sludge (AS) biomass (which is the source of BPO in AD of WAS) releases higher N, and significantly higher P and metals for cases where PAOS are present in the WAS. The extent to which the active biomass (OHO and PAOs) is present in the AD of WAS depends on the operation of the parent AS system. In South Africa, amongst other countries, the AS system sludge age is usually high to allow for sufficient time in degradation of influent sewage organics and nutrients and to promote the generation of effluent that meets the strict discharge regulations. However, the systems with high sludge retention times contain reduced active biomass concentration in the WAS, hence fewer quantities of BPO to be converted to biogas in AD - hence the AD of WAS from parent AS systems operated at high solids retention times is generally not recommended (Ekama, 2017). If the sludge age of the parent AS system is lower, the active biomass fraction in WAS is higher and more methane can be generated from the AD of the WAS. However, higher ammonia and phosphates concentrations released in the process find their way to the dewatering liquor. This is especially significant for AS systems with enhanced biological phosphorus removal (EBPR), whereby the P (and also metals – i.e., Mg, K and Ca that formed the polyphosphate inside the PAO biomass) are released in much higher quantities. For such a case, the WAS shall require to be thickened in dissolved air floatation units before AD (to avoid struvite precipitation during the thickening process) and the AD may require careful operation that anticipates potential struvite precipitation (the precipitation process would lower AD pH).

Table 6-2: Dewatering liquor composition (mg/l) for plants A, B, and C for the option of treating 100% of the AD DWL

	Plant A			Plant B			Plant C		
Parameter	AD	BABE	Struvite	AD	BABE	Struvite	AD	BABE	Struvite
COD	70.00	70.00	70.00	52.00	52.00	52.00	32.76	32.76	32.76
FSA	255	9.01	175	287	9.01	155	231	9.01	180

	Plant A			Plant B			Plant C		
OrthoP	162	507	53.01	460	349	150	0.00	0.00	0.00

The BABE and struvite precipitation processes result in lowered N and P nutrients, respectively (Table 6-2). Following the AD of enhanced biological phosphorus removal (EBPR) WAS that contains high P and metals, struvite precipitation process, rather than BABE would be preferred because the BABE process would not be able to remove the excess P that would end up being recycled back to the AS system and may eventually result in poor effluent quality (high P). Otherwise, the option of recycling the P back to the AS system (i.e., after BABE process) may require dosage of acetate in the anaerobic zone of the AS system to remove the excess P that came with the DWL. However, this is a significant operational cost and may result in increased sludge production (from growth of polyphosphate accumulating organisms (PAO) biomass), which may in turn pose a threat to the capacity of the system (i.e. the design volume and secondary settling tank surface area allowed to cater for a specified maximum total solid concentration). If struvite precipitation is used as the STP, then maintenance of high pH and ensuring the presence of usually limiting components such as magnesium would be necessary for maximum P recovery as struvite. Apart from P recovery, the utilisation of struvite precipitation as SSTP, rather than recycling of the dewatering liquor, would result in lower nitrification oxygen demand in the parent AS system. This is due to some ammonia being used towards struvite ($MgNH_4PO_4.6H_2O$) the precipitation process. However, ammonia is usually not the limiting component of the precipitation reaction – the precipitation of struvite usually gets limited by the quantity of magnesium present, with the acceptance of pH being maintained at high value of above 7. Hence the effluent from the struvite precipitation reaction may still have some ammonia while that from the BABE process (which specifically removes large quantities of ammonia) is low. This is the cause for the EQI being lower for the system with the BABE process in plant A and C. Hence, although side-stream processes would be recommended for treatment of dewatering liquor- the type of sludge digested, and the operation of the SSTP becomes significant.

6.2.3 Effluent Quality

The incorporation of a STP in the wastewater treatment route improves the effluent quality. Table 6-3 compares the effluent concentration for different wastewater constituents for plants A, B and C with the effluent quality special limit standards adapted from Department of Water Affairs (National Water Act, No. 36 of 1998, as amended, 2013). The values highlighted in red are those where the special limit standards are exceeded. The increase in the effluent phosphate (PO_4) (plants A and C) and nitrate (NO_3) concentrations (plants B and C) is due to dilution effects. Figure 6-1 to Figure 6-3, further, elaborates on the benefits of integrating SSTP in the wastewater treatment layout with respect to effluent quality and operational cost.

Table 6-3: Effluent quality (mg/l) for plants A, B and C

		Plant A			Plant B			Plant C		
Parameter	Effluent Quality	No SSTP	BABE	Struvite	No SSTP	BABE	Struvite	No SSTP	BABE	Struvite
COD	30.00	70.00	70.00	70.00	52.00	52.00	52.00	32.76	32.76	32.76
Ammonia	2.00	2.20	2.20	2.20	2.20	2.10	2.20	0.60	0.60	0.60
NO3	1.50	5.19	4.76	4.75	6.14	6.72	6.79	5.49	6.08	6.17
PO4	2.50	0.89	1.16	0.91	12.17	8.91	6.74	1.13	1.43	1.43

6.2.4 Plant Performance

Both the effluent quality and operational cost indices (EQI and OCI, respectively) decrease with an increase in the percentage of DWL treated in the STP (see Figure 6-1 to Figure 6-3). The EQI varies with respect to SSTP use for the plants under consideration i.e., for plants A and B, the struvite precipitation achieves lower EQI for the percentage of 40% and above of treated DWL; however, for plant C, the BABE process achieves a lower EQI. The BABE process achieves lower OCI than struvite precipitation process this is because the former process uses the same quantity of oxygen in the breakdown of ammonia (conversion to nitrates) from the dewatering liquor and furthermore oxygen for endogenous process for biomass added to the BABE process from the AS system. On the other hand, struvite precipitation uses ammonia directly (from aqueous NH_4^+ to solid-phase struvite, $MgNH_4PO_4.6H_2O$) without imposing significant increase in aeration energy requirements.

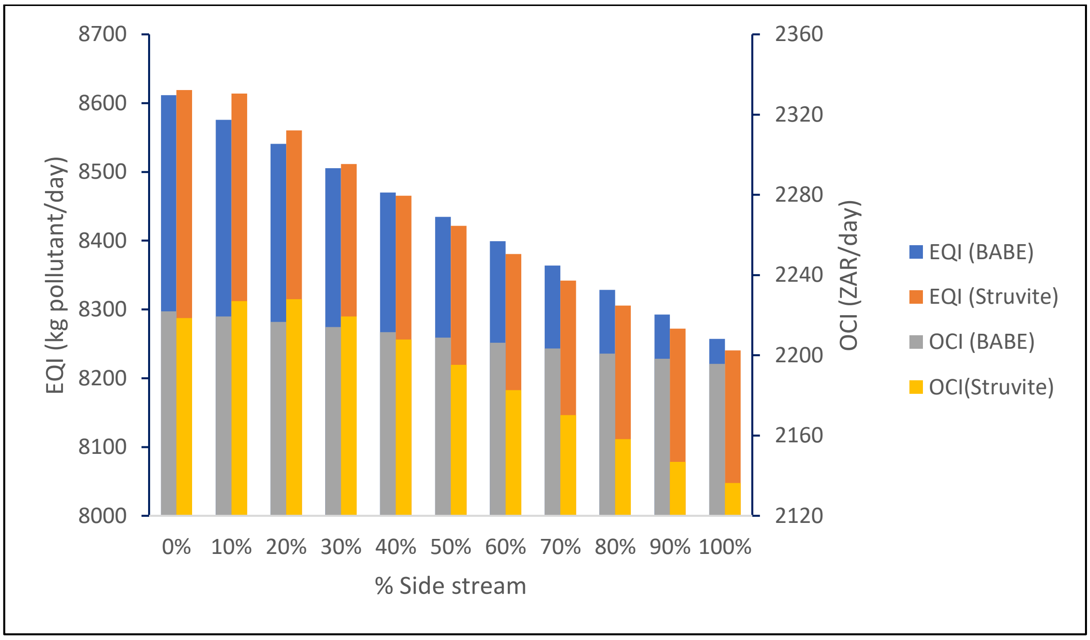

Figure 6-1: EQI and OCI variation with the percentage of dewatering liquor treated for plant A

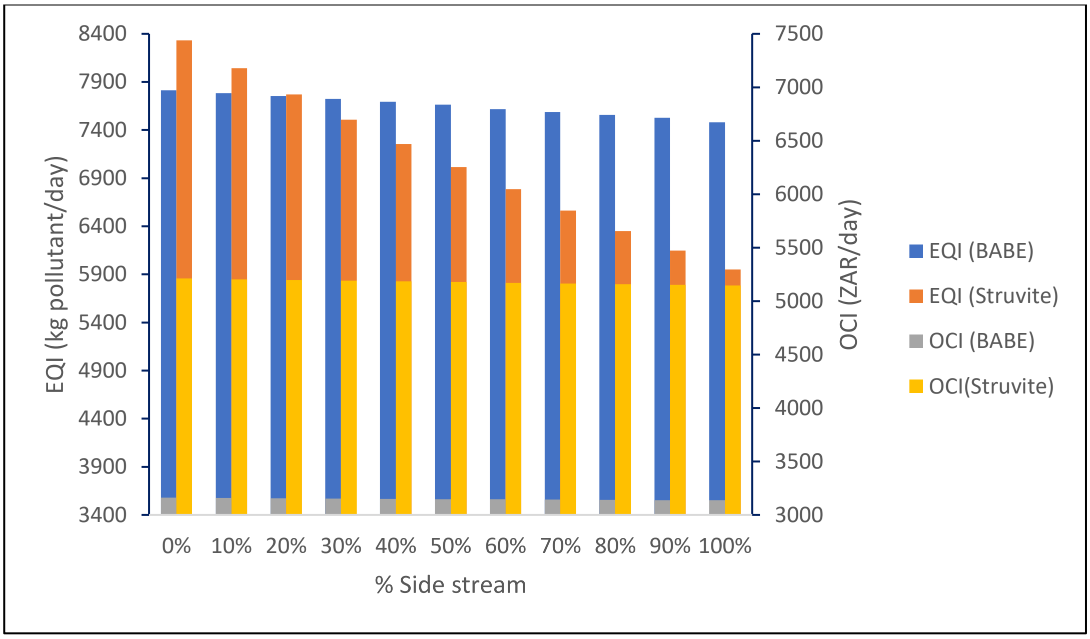

Figure 6-2: EQI and OCI variation with the percentage of dewatering liquor treated for plant B

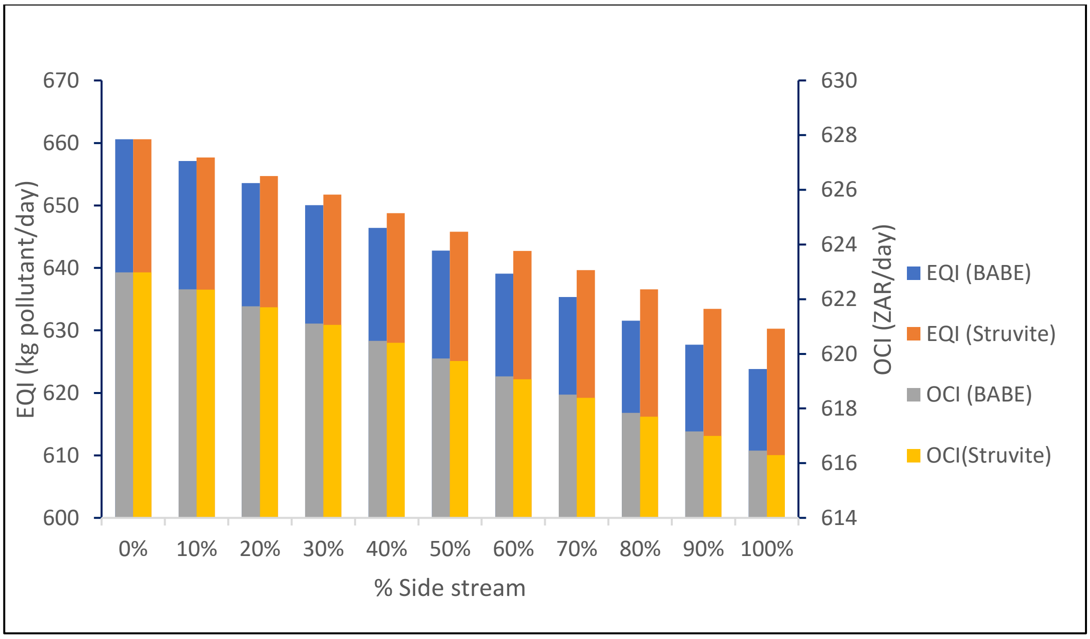

Figure 6-3: EQI and OCI variation with the percentage of dewatering liquor treated for plant C

6.2.5 Recommendation

The recommendation of the suitable SSTP depends on the composition of the DWL. Following the anaerobic digestion (AD) of enhanced biological phosphorus removal (EBPR) waste activated sludge (WAS) that contains high P and metals, the SSTP of struvite precipitation, rather than BABE would be preferred because the BABE process would not be able to remove the excess P that would end up being recycled back to the activated sludge (AS) system and may eventually result in poor effluent quality (high P). The option of recycling the P back to the AS system may require dosage of acetate in the anaerobic zone of the AS system to remove the excess P that came with the dewatering liquor. However, this is a significant operational cost and may result in increased sludge production (from growth of PAO biomass), which may, in turn, pose a threat to the capacity of the system (i.e., the design volume and secondary settling tank surface allowed to cater for a specified maximum total solid concentration). If struvite precipitation is used as the SSTP, then maintenance of high pH and ensuring the presence of usually limiting components such as magnesium would be necessary for maximum P recovery as struvite. For DWL from an AD treating WAS that is not P rich (i.e., with low EBPR), the recommended SSTP operation would be the BABE process rather than the struvite precipitation. This is unless the P released is significantly high to be recovered via dosage of magnesium towards struvite precipitation. For the purposes of the plant performance evaluation tool (PPET), the EQI was given a higher weight (60%) than the OCI (40%) because the primary objective of a WWTP is to achieve better effluent quality. The struvite precipitation process is recommended for EBPR layouts, namely UCT (plant A) and JHB (Plant C) layouts because these configurations release higher P concentration in the dewatering liquor. The BABE process is recommended for the nitrification-denitrification layout, namely the 3-Stage Phoredox layout (plant B).

The benefits of side-stream treatment would depend on the selected unit process for implementation. However, it is notable that when the parent AS system is at capacity, the implementation of SSTPs is strongly recommended to ensure effluent quality (which is the priority for waste treatment systems). If the AS treatment system is over capacity, then the tool (PPET) may be used to determine whether the utilisation of a SSTP may result in further benefits such as lower oxygen consumption (where struvite recovery is implemented to remove ammonia and P) and better effluent quality (where the ammonia is too high in the influent and a side-stream process system such as BABE would be useful towards augmented N removal).

6.3 Closure

The results generated from the developed tool and the steady state model of Ekama (2009) were useful in examining whether the objectives of the tool development were met. The complex steady-state WWTP models were simplified into a simple evaluative WRRF tool without compromising the generated results. There were negligible discrepancies between the results of the plant performance evaluation tool and those of the models developed by Ekama (2009), consequently, this increased the confidence in the developed tool. The developed tool, PPET, was used to run case studies using South African WWTPs. It was proven that there is an added benefit of incorporating side-stream treatment process into the mainstream WWTP processes. The incorporation of BABE and struvite precipitation processes results in a lowered minimum sludge age and oxygen demand in the biological reactor. Consequently, WWTP configurations with incorporated SSTPs generate better effluent quality and lower operational costs. The struvite precipitation process is recommended to be incorporated in EBPR configurations such as the UCT and JHB layouts while the BABE process is suited for nitrification-denitrification configurations such as 3-stage Phoredox.

7. Conclusions and Recommendations

7.1 Introduction

The objectives of this research project were to:

- Simplify complex full-scale WWTP models into a user-friendly WRRF steady-state that evaluates the impact of recycling dewatering liquors on the overall WWTP performance. The plant performance was evaluated based on two performance indices, namely, effluent quality and operational cost indices, EQI and OCI, respectively. Furthermore, the developed tool incorporates either of the two-side stream treatment process (SSTP) i.e., bio-augmentation batch enhanced (BABE) and struvite precipitation. These processes were selected because they are the most suitable for South African operating conditions. Although there are several technologies for nitrogen removal, such as SHARON, ANNAMOX and CANON, the BABE process was found to be the most suitable because it appears to be a low-cost method for nitrogen removal (i.e., lower investment and operational costs). Additionally, there are several methods of P removal, in the form of struvite, from the dewatering liquors such as conventional coagulation, flocculation and sedimentation using metal-salts. Although for South African market, struvite recovery and application is not cost-effective compared to conventional method chemical precipitation methods, it was chosen as a prospective method for P removal because there is a potential in the environmental and economic benefits in the application of struvite sub-products such as in agriculture (fertiliser), animal food industries and construction materials.
- The second objective was to compare the results from the developed simplified steady-state mathematical evaluation tool (PPET – plant performance evaluation tool) to those of validated steady-state model. The aim of this objective was to build confidence in the outcomes of PPET.
- The last objective was to use PPET to run case studies on South African plants with the intent of showing the applicability and capability of the developed tools.

7.2 Conclusions

In conclusion, the complex steady-state WWTP mathematical models were simplified into a simple plant-wide evaluative WRRF tool, namely, PPET which enables stakeholders to run different scenarios and enable them to make educated choices. This tool was not developed to be used for design but rather for evaluation and education purposes, therefore, it needs to be developed in further studies. It is, however, concluded that the objectives of this research project were met through the developed tool: (i) the results generated from PPET compare well with those from validated steady-state models, hence the simplification of the WWTP complex models does not compromise the results generated; (ii) the user-interface of PPET enables the bridging of the gap between the lack of expertise in using WRRF models by the newly interested stakeholders and the complexity of these models; (iii) furthermore, the incorporation of SSTP in the mainstream WWTP process proved the fact that DWL have an impact of the overall plant performance i.e., plant that incorporated a SSTP in their configuration proved to have an additional benefit in producing better effluent quality at lower operational costs; EQI and OCI decreases with an increase in the percentage of dewatering liquor that is treated in the SSTP, hence better plant performance; (iv) lastly, PPET was used to run several case studies proving the potential of using modelling tools to assist in decision making and in evaluating wastewater plant performance.

7.3 Recommendations

The following recommendations were made based on the discussions and conclusions of this research project for future improvement on PPET or development of other WRRF tools:

- It is recommended that for future tool (PPET) improvements, a separation of WAS and PS digestion should be considered i.e., PS to be digested in the anaerobic digester and WAS in the anoxic-aerobic reactor. The developed tool (PPET) combines the anaerobic digestion of both WAS and PS. However, there is no added benefit for digesting both of these sludges together in the anaerobic digester unless P recovery is a requirement.
- It is recommended that further evaluative indices should be incorporated in the future version of the tool. Currently, only two evaluative indices, namely the effluent quality index (EQI) and operational cost index (OCI), were considered. For improvement, greenhouse gas indices

can be added (factored into the equations) as well. This is important because treatment plant emits a large amount greenhouse gas.

- It is recommended that other SSTPs should be incorporated in the tool. The developed tool current has only two SSTPs specifically, bio-augmentation batch enhanced (BABE) and struvite precipitation processes. For further development, other SSTPs such as anaerobic ammonium oxidation (ANNAMOX) can be added into this tool to give the user a range of options to compare from.
- Lastly, it is evident that due to differences in treatment systems (i.e., with variations in influent loads, system configurations and priority end products required - energy, water, phosphorus, etc.) further investigations are required on strategies for implementation of the various SSTPs. For instance, the steady-state model (PPET) as a decision-making tool is not capable of predicting the actual cost value for recovery of struvite (because this depends on size of crystals and market demand among other factors that require much more complex models) through dosage of magnesium in the SSTP.

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Appendix A : Questionnaire

Converting WRRF Steady State Mathematical Model into a Design Evaluation Tool

Questionnaire

1. To what level do you understand the technical operations of a wastewater treatment plant?

Poor	Fair	Satisfactory	Very Good	Excellent
O	O	O	O	O

2. Once opened, how difficult/easy is it to navigate the interface of the tool?

Quite difficult	Slightly difficult	Neutral	Quite easy	Very easy
O	O	O	O	O

3. How easy is it to obtain the parameters and inputs of the wastewater treatment plant required by the tool?

Quite difficult	Slightly difficult	Neutral	Quite easy	Very easy
O	O	O	O	O

4. Does it take long to complete the inputs and parameters section of the tool?

Quite long	Slightly long	Neutral	Quite short	Very short
O	O	O	O	O

5. Did the model run to completion?

Yes	No
O	O

6. Did the results obtained make sense?

Yes Slightly No

O O O

If you did not answer yes, please provide further comments:

7. Was there any information that the user expected but did not obtain?

Yes No

O O

General comments:

8. What challenges did you experience with the tool?

Comments:

9. Was the information obtained by the user deemed useful?

Yes No

O O

10. What did you find helpful from the obtained results?

General comments:

11. Did you learn anything new with continued exposure to the tool?

Yes No

O O

12. Do you see this tool being of benefit to your organization?

Yes	No
O	O

If yes, how?

Appendix B: Questionnaire Responses

Converting WRRF Steady State Mathematical Model into a Design Evaluation Tool Questionnaire

1. To what level do you understand the technical operations of a wastewater treatment plant?

Poor	Fair	Satisfactory	Very Good	Excellent
O	O	O	X	O

2. Once opened, how difficult/easy is it to navigate the interface of the tool?

Quite difficult	Slightly difficult	Neutral	Quite easy	Very easy
O	O	X	O	O

3. How easy is it to obtain the parameters and inputs of the wastewater treatment plant required by the tool?

Quite difficult	Slightly difficult	Neutral	Quite easy	Very easy
O	O	O	X	O

4. Does it take long to complete the inputs and parameters section of the tool?

Quite long	Slightly long	Neutral	Quite short	Very short
O	O	X	O	O

5. Did the model run to completion?

Yes	No
X	O

6. Did the results obtained make sense?

Yes	Slightly	No
O	O	X

If you did not answer yes, please provide further comments:

- THE SYSTEM DOES NOT PROVIDE RECOMMENDATIONS.

7. Was there any information that the user expected but did not obtain?

Yes	No
X	O

General comments:

- I EXPECTED RECOMMENDATIONS ON HOW TO OPTIMIZE THE PLANT.

8. What challenges did you experience with the tool?

Comments:

- I DIDNT HAVE CHALLENGES WITH THE TOOL, I WAS EXPECTING RECOMMENDATIONS FROM DIFFERENT CONFIGURATIONS.

9. Was the information obtained by the user deemed useful?

   Yes O No ☒

10. What did you find helpful from the obtained results?

    General comments:

    -THE TOOL WAS NOT HELPFUL.

11. Did you learn anything new with continued exposure to the tool?

    Yes ☒ No O

12. Do you see this tool being of benefit to your organization?

    Yes O No ☒

    If yes, how?

Converting WRRF Steady State Mathematical Model into a Design Evaluation Tool Questionnaire

1. To what level do you understand the technical operations of a wastewater treatment plant?

Poor	Fair	Satisfactory	Very Good	Excellent
O	O	O	√	O

2. Once opened, how difficult/easy is it to navigate the interface of the tool? Quite difficult

Quite difficult	Slightly difficult	Neutral	Quite easy	Very easy
O	O	O	√	O

3. How easy is it to obtain the parameters and inputs of the wastewater treatment plant required by the tool?

Quite difficult	Slightly difficult	Neutral	Quite easy	Very easy
O	O	√	O	O

4. Does it take long to complete the inputs and parameters section of the tool?

Quite long	Slightly long	Neutral	Quite short	Very short
O	O	√	O	O

5. Did the model run to completion?

Yes	No
√	O

6. Did the results obtained make sense?

Yes	Slightly	No	I don't know
O	√	O	O

If you did not answer yes, please provide further comments:

Some of the graphs were a bit obtuse.

7. Was there any information that the user expected but did not obtain?

Yes No

✓ O

General comments:

Compliance with standards for each option would have good to see, specifically for nutrient limits.

8. What challenges did you experience with the tool?

Comments:

Some of the inputs were not well defined (Didn’t have the manual at the time so this may be a moot point)

9. Was the information obtained by the user deemed useful?

Yes No

✓ O

10. What did you find helpful from the obtained results? General comments:

Useful as a general quick assessment tool

11. Did you learn anything new with continued exposure to the tool?

Yes No

O ✓

If Yes, please briefly state what you learned.

12. Do you see this tool being of benefit to your organization?

Yes No

✓ O

If yes, please briefly state how?

With a bit of tweaking this could be a useful tool for decision support. Not just for selection of a side stream treatment but also as a general control verification, e.g. sludge age.

Converting WRRF Steady State Mathematical Model into a Design Evaluation Tool

Questionnaire

1.To what level do you understand the technical operations of a wastewater treatment plant?

Poor	Fair	Satisfactory	Very Good	Excellent
O	O	O	**X**	O

2.Once opened, how difficult/easy is it to navigate the interface of the tool? Quite difficult

Quite difficult	Slightly difficult	Neutral	Quite easy	Very easy
O	O	O	X	O

3.How easy is it to obtain the parameters and inputs of the wastewater treatment plant required by the tool?

Quite difficult	Slightly difficult	Neutral	Quite easy	Very easy
O	**X**	O	O	O

4.Does it take long to complete the inputs and parameters section of the tool?

Quite long	Slightly long	Neutral	Quite short	Very short
O	O	**X**	O	O

5.Did the model run to completion?

Yes	No
X	O

6.Did the results obtained make sense?

Yes	Slightly	No	I don't know
O	**X**	O	O

If you did not answer yes, please provide further comments:

The prepopulated model input and output results made sense, and specifically the characterization for the raw and settled wastewater.

Unfortunately, could not determine results with own set of data.

7.Was there any information that the user expected but did not obtain?

Yes No

O **X**

General comments:

Cannot determine, as the model did not run to completion.

8.What challenges did you experience with the tool?

Comments:

Data input could not occur due to error (screen shot supplied later)

9.Was the information obtained by the user deemed useful?

Yes No

X O

The provided simulation (Waterval WWTP) indicated that once the simulation model is fully functional, useful information will be obtained.

10.What did you find helpful from the obtained results?

General comments:

The provided simulation (Waterval WWTP) indicated that once the simulation model is fully functional, useful information will be obtained with regards to process performance.

11.Did you learn anything new with continued exposure to the tool?

Yes No

X O

If Yes, please briefly state what you learned.

The performance indices incorporated in the tool should be developed as a municipal treatment indicator benchmark. Both the effluent quality index (EQI) and the operational cost index (OCI) add value to plant performance evaluation and the tool.

12.Do you see this tool being of benefit to your organization?

Yes No

X O

If yes, please briefly state how?

Plant managers and other stakeholders will be able to simulate their plants with available information. The tool is well documented to guide users with limited modelling experience. The raw and settled sewage characterization is detailed and will add value to the knowledge base for each plant.

Questions / Remarks:

1.Population definition – provide more information

2.Temperature range usually 14-24 °C according to WRC guidelines

3.Reactor fractions cannot all be 0-1 range

4.DSVI not correct range (50-200ml/g; >150ml/g = bulking sludge)

5.Fraction of Qi to Module 1, Qi definition

6.Why different units (although same basis) referenced for raw and settled sewage (raw mg/l and settled g/m3)

7.User manual editing required:

The consist of combining the sludge dewatering liquor with a fraction of the return activated sludge from the BNR reactor into a nitrifying batch reactor with short retention time.

The Modified Ludzack-Ettinger BNR layout consists of two reactors in series; an anoxic and aerobic reactor as shown in figure 1. **(Actually Figure 3)**

The influent is treated through anoxic and aerobic reactors an effluent with low nitrogen content can be achieved. **(Missing words)**

Converting WRRF Steady State Mathematical Model into a Design Evaluation Tool Questionnaire

1. To what level do you understand the technical operations of a wastewater treatment plant?

Poor	Fair	Satisfactory	Very Good	Excellent
O	O	O	O	O

2. Once opened, how difficult/easy is it to navigate the interface of the tool?

Quite difficult	Slightly difficult	Neutral	Quite easy	Very easy
O	O	O	O	O

3. How easy is it to obtain the parameters and inputs of the wastewater treatment plant required by the tool?

Quite difficult	Slightly difficult	Neutral	Quite easy	Very easy
O	O	O	O	O

4. Does it take long to complete the inputs and parameters section of the tool?

Quite long	Slightly long	Neutral	Quite short	Very short
O	O	O	O	O

5. Did the model run to completion?

Yes	No
O	O

6. Did the results obtained make sense?

Yes	Slightly	No	I don't know
O	O	O	O

If you did not answer yes, please provide further comments:

Outputs in results page do not look right
NH_4 > TKN NO_3 0,8mg/l etc

7. Was there any information that the user expected but did not obtain?

Yes	No
O	O

General comments:

Effect of sidestream treatment

8. What challenges did you experience with the tool?

Comments:

None

9. Was the information obtained by the user deemed useful?
   Yes ✓ No O   subject to comments in Q6 & 7

10. What did you find helpful from the obtained results?
    General comments:

11. Did you learn anything new with continued exposure to the tool?
    Yes O No ✓
    If Yes, please briefly state what you learned.

12. Do you see this tool being of benefit to your organization?
    Yes ✓ No O
    If yes, please briefly state how?

When completed outputs will be useful

Inclusion of three stage ~~stag~~ Phoredox,

a very common system should be included

Appendix C Measurements

Table A-1: Influent settled wastewater measurements and predicted (i.e., estimated and fitted) values

	COD (mgCOD/l)			**TKN (mgTKN/l)**			**TP (mgTP/l)**			**TSS (mgTSS/l)**		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2015/09/01		798	986		81	70		15	10		261	164
2015/09/02		733	853		75	56		14	9		240	231
2015/09/03		610	694		62	50		12	7		200	187
2015/09/04	0	647	749		66	50		12	9		212	192
2015/09/05		319	380		33	36		6	4		105	52
2015/09/06		562	663		57	44		11	6		184	164
2015/09/07		689	823		70	53	0	13	8		226	189
2015/09/08		528	645		54	49		10	7		173	93
2015/09/09		678	763		69	55		13	8		222	194
2015/09/10		524	638		54	51		10	7		172	96
2015/09/11		959	1198		98	77		18	12		314	207
2015/09/12		866	951		88	62		16	11		284	282

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2015/09/13		516	600		53	47		10	7		169	148
2015/09/14	782	338	422	40,9	35	46	3,8	6	4	204	111	6
2015/09/15		743	817		76	54		14	9		243	242
2015/09/16		920	947		94	54		17	9		301	296
2015/09/17		608	959		62	65		12	8		199	100
2015/09/18		501	531		51	46		9	6		164	165
2015/09/19		924	1091		94	61		18	9		302	309
2015/09/20		1038	1296		106	72		20	11		340	280
2015/09/21	1106	859	693	59	88	49	2,8	16	5	286	281	164
2015/09/22		605	626		62	46		11	7		198	214
2015/09/23		661	725		67	54		13	8		216	211
2015/09/24		668	820		68	58		13	8		219	109
2015/09/25		450	456		46	47		9	7		147	149
2015/09/26		437	451		45	43		8	7		143	144
2015/09/27		734	919		75	61		14	8		240	182

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2015/09/28	551	428	542	68,5	44	51	6,4	8	7	123	140	124
2015/09/29		286	329		29	38		5	5		94	48
2015/09/30		1056	1193		108	59		20	10		346	299
2015/10/01		968	1197		99	81		18	10		317	159
2015/10/02		510	614		52	46		10	6		167	139
2015/10/03		505	562		52	44		10	6		165	157
2015/10/04		835	1047		85	66		16	9		273	171
2015/10/05	821	561	726	54,4	57	54	6,1	11	7	145	184	145
2015/10/06		367	362		38	34		7	6		120	129
2015/10/07		437	421		45	37		8	4		143	126
2015/10/08		780	965		80	62		15	8		255	128
2015/10/09		373	453		38	39		7	5		122	80
2015/10/10		425	533		43	35		8	4		139	93
2015/10/11		402	408		41	42		8	6		132	143
2015/10/12	1171	533	791	55,5	54	58	7,9	10	8	93	175	93

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2015/10/13		972	1208		99	74		18	10		318	159
2015/10/14		868	1018		89	66		16	9		284	172
2015/10/15		612	756		63	47		12	7		200	165
2015/10/16		736	859		75	56		14	8		241	220
2015/10/17		840	1062		86	62		16	9		275	205
2015/10/18		557	684		57	49		11	6		182	91
2015/10/19	543	421	562	65	43	54	8,3	8	7	170	138	137
2015/10/20		825	1033		84	65		16	10		270	182
2015/10/21		555	600		57	50		11	6		182	123
2015/10/22		1083	2048		111	106		21	14		355	177
2015/10/23		369	443		38	40		7	5		121	64
2015/10/24		530	605		54	49		10	7		173	156
2015/10/25		839	1433		86	80		16	13		275	137
2015/10/26	803	475	627	59,5	48	56	4,7	9	6	97	155	85
2015/10/27		456	549		47	45		9	7		149	75

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2015/10/28		367	406		38	40		7	5		120	60
2015/10/29		461	563		47	40		9	6		151	121
2015/10/30		575	706		59	49		11	7		188	94
2015/10/31		793	1147		81	71		15	10		260	121
2015/11/01		664	760		68	55		13	10		217	193
2015/11/02	535	496	636	69,5	51	59	12,5	9	9	37	162	74
2015/11/03		739	920		75	60		14	9		242	153
2015/11/04		444	549		45	47		8	6		145	76
2015/11/05		762	943		78	64		14	10		250	145
2015/11/06		1009	1268		103	70		19	11		330	269
2015/11/07		752	872		77	56		14	9		246	226
2015/11/08		1027	1276		105	78		19	11		336	168
2015/11/09	572	521	608	62	53	55	7,4	10	8	105	170	95
2015/11/10		482	526		49	46		9	7		158	143
2015/11/11		515	351		53	35		10	6		169	182

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2015/11/12		582	696		59	58		11	6		190	160
2015/11/13		548	627		56	48		10	6		180	164
2015/11/14		555	596		57	48		11	7		182	180
2015/11/15		472	462		48	40		9	5		155	175
2015/11/16	516	535	540	0	55	46	0	10	8	168	175	164
2015/11/17		498	569		51	44		9	6		163	135
2015/11/18		963	1103		98	64		18	9		315	225
2015/11/19		811	1004		83	58		15	9		266	253
2015/11/20		553	553		57	58		10	11		181	177
2015/11/21		519	573		53	45		10	7		170	162
2015/11/22		1016	1269		104	74		19	10		333	166
2015/11/23	409	458	451	55,5	47	45	5,3	9	6	102	150	98
2015/11/24		639	787		65	63		12	8		209	162
2015/11/25		477	580		49	50		9	7		156	107
2015/11/26		638	794		65	55		12	7		209	139

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2015/11/27		514	623		52	48		10	7		168	84
2015/11/28		562	684		57	51		11	7		184	92
2015/11/29		710	881		73	60		13	9		232	145
2015/11/30	503	786	596	59,5	80	48	6	15	7	97	257	125
2015/12/01		721	897		74	56		14	8		236	190
2015/12/02		596	756		61	54		11	7		195	138
2015/12/03		757	949		77	53		14	8		248	202
2015/12/04		385	460		39	41		7	5		126	63
2015/12/05		447	528		46	44		8	6		146	121
2015/12/06		428	458		44	39		8	8		140	130
2015/12/07	732	659	688	48,1	67	56	8,3	12	9	199	216	197
2015/12/08		472	531		48	46		9	7		155	138
2015/12/09		529	661		54	58		10	7		173	105
2015/12/10		403	479		41	47		8	6		132	82
2015/12/11		477	572		49	50		9	7		156	87

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2015/12/12		505	603		52	46		10	8		165	133
2015/12/13		758	930		77	63		14	10		248	124
2015/12/14	498	466	533	59	48	51	6,3	9	7	45	152	74
2015/12/15		545	636		56	48		10	7		178	155
2015/12/16		412	519		42	38		8	5		135	102
2015/12/17		424	491		43	45		8	6		139	116
2015/12/18		283	335		29	34		5	5		92	64
2015/12/19		441	517		45	45		8	6		145	120
2015/12/20		421	509		43	45		8	6		138	87
2015/12/21	395	376	477	54	38	47	5,3	7	6	41	123	56
2015/12/22		251	277		26	29		5	4		82	72
2015/12/23		446	542		46	43		8	6		146	73
2015/12/24		373	451		38	40		7	6		122	86
2015/12/25		270	259		28	28		5	4		88	96
2015/12/26		293	329		30	32		6	5		96	83

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2015/12/27		226	233		23	26		4	4		74	71
2015/12/28		177	173		18	23		3	3		58	58
2015/12/29		334	334		34	29		6	4		109	119
2015/12/30		328	324		33	31		6	5		107	116
2015/12/31		339	346		35	35		6	6		111	111
2016/01/01		312	341		32	36		6	5		102	90
2016/01/02		309	345		32	28		6	4		101	93
2016/01/03		354	372		36	24		7	3		116	126
2016/01/04	501	367	485	0	37	38	0	7	6	0	120	109
2016/01/05		539	671		55	46		10	7		176	125
2016/01/06		320	392		33	38		6	4		105	84
2016/01/07		317	372		32	37		6	5		104	52
2016/01/08		440	524		45	40		8	6		144	119
2016/01/09		330	408		34	31		6	4		108	78
2016/01/10		327	404		33	25		6	4		107	54

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2016/01/11	482	303	421	33,6	31	31	5,1	6	4	77	99	81
2016/01/12		400	481		41	35		8	5		131	110
2016/01/13		425	466		43	35		8	5		139	70
2016/01/14		642	800		66	48		12	7		210	108
2016/01/15		411	502		42	40		8	5		135	78
2016/01/16		528	661		54	43		10	6		173	130
2016/01/17		589	722		60	51		11	7		193	96
2016/01/18	523	691	757	46,3	71	50	4,3	13	7	41	226	82
2016/01/19		138	99		14	21		3	3		45	58
2016/01/20		612	732		62	45		12	6		200	100
2016/01/21		843	1114		86	56		16	8		276	138
2016/01/22		289	348		30	32		5	4		95	73
2016/01/23		300	365		31	31		6	4		98	67
2016/01/24		371	412		38	31		7	5		122	116
2016/01/25	282	276	305	29,2	28	26	3,1	5	3	42	90	44

Time (days)	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2016/01/26		324	371		33	29		6	4		106	95
2016/01/27		466	447		48	29		9	4		153	148
2016/01/28		396	478		40	36		7	5		130	106
2016/01/29		437	496		45	36		8	5		143	133
2016/01/30		357	431		36	35		7	5		117	58
2016/01/31		352	430		36	35		7	5		115	84
2016/02/01	574	546	509	38,7	56	38	3,3	10	5	88	179	87
2016/02/02		407	490		42	39		8	6		133	67
2016/02/03		534	532		55	37		10	5		175	105
2016/02/04		587	727		60	47		11	7		192	98
2016/02/05		539	605		55	41		10	7		177	169
2016/02/06		412	587		42	43		8	6		135	67
2016/02/07		445	542		45	41		8	6		146	75
2016/02/08	457	401	475	40,2	41	38	4,7	8	5	54	131	64
2016/02/09		557	689		57	45		11	6		182	91

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2016/02/10		408	505		42	39		8	5		134	67
2016/02/11		586	718		60	46		11	8		192	156
2016/02/12		503	592		51	41		10	7		165	141
2016/02/13		312	368		32	34		6	6		102	51
2016/02/14		396	487		40	38		8	6		130	89
2016/02/15	433	411	472	65,5	42	38	5,3	8	5	72	135	73
2016/02/16		335	404		34	33		6	5		110	87
2016/02/17		312	370		32	40		6	4		102	51
2016/02/18		421	504		43	39		8	7		138	108
2016/02/19		278	273		28	25		5	4		91	100
2016/02/20		269	308		28	26		5	3		88	78
2016/02/21		380	461		39	39		7	5		124	78
2016/02/22	378	330	291	29,5	34	32	3,8	6	4	42	108	65
2016/02/23		602	733		61	47		11	7		197	164
2016/02/24		636	736		65	49		12	7		208	104

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2016/02/25		600	765		61	40		11	6		196	142
2016/02/26		308	336		31	29		6	4		101	96
2016/02/27		328	383		33	32		6	4		107	91
2016/02/28		517	641		53	44		10	6		169	105
2016/02/29	373	441	386	36,7	45	36	3,9	8	5	70	144	70
2016/03/01		476	573		49	47		9	7		156	124
2016/03/02		397	454		41	39		8	5		130	120
2016/03/03		442	542		45	41		8	6		145	82
2016/03/04		429	526		44	37		8	5		140	114
2016/03/05		274	320		28	34		5	4		90	49
2016/03/06		362	443		37	35		7	4		119	67
2016/03/07	372	392	384	44,9	40	41	4,7	7	5	64	128	63
2016/03/08		539	662		55	46		10	7		177	141
2016/03/09		525	633		54	49		10	7		172	139
2016/03/10		353	360		36	37		7	7		115	110

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2016/03/11		363	453		37	31		7	4		119	96
2016/03/12		294	358		30	28		6	4		96	48
2016/03/13		378	592		39	40		7	5		124	62
2016/03/14	666	541	746	54	55	46	12,1	10	7	264	177	184
2016/03/15		587	738		60	46		11	7		192	140
2016/03/16		435	510		44	36		8	5		142	111
2016/03/17		390	451		40	29		7	4		128	119
2016/03/18		110	184		11	10		2	2		36	72
2016/03/19		203	181		21	15		4	4		66	78
2016/03/20		260	322		27	24		5	3		85	66
2016/03/21	173	226	168	0	23	22	0	4	3	34	74	36
2016/03/22		269	252		28	26		5	4		88	100
2016/03/23		280	296		29	29		5	4		92	99
2016/03/24		405	504		41	36		8	5		133	89
2016/03/25		238	284		24	27		5	4		78	48

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2016/03/26		329	376		34	33		6	5		108	93
2016/03/27		486	600		50	37		9	6		159	131
2016/03/28	402	444	421	36,7	45	34	3,2	8	5	90	145	81
2016/03/29		521	651		53	45		10	6		171	125
2016/03/30		247	250		25	27		5	4		81	91
2016/03/31		621	769		63	52		12	7		203	110
2016/04/01		626	771		64	52		12	7		205	102
2016/04/02		358	439		37	35		7	5		117	78
2016/04/03		289	289		30	33		5	5		95	95
2016/04/04	581	709	640	52	72	48	6,4	13	7	140	232	134
2016/04/05		467	571		48	45		9	7		153	95
2016/04/06		658	798		67	50		12	7		215	142
2016/04/07		492	569		50	36		9	5		161	151
2016/04/08		385	423		39	34		7	5		126	122
2016/04/09		438	478		45	36		8	5		143	143

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2016/04/10		343	408		35	37		6	5		112	56
2016/04/11	421	451	430	37,5	46	38	5,4	9	5	90	148	89
2016/04/12		566	710		58	47		11	7		185	138
2016/04/13		688	843		70	51		13	8		225	182
2016/04/14		591	686		60	46		11	8		193	173
2016/04/15		623	698		64	40		12	6		204	210
2016/04/16		596	691		61	44		11	7		195	179
2016/04/17		633	761		65	49		12	9		207	174
2016/04/18	522	551	452	32,8	56	36	3,6	10	5	80	180	88
2016/04/19		538	664		55	43		10	7		176	142
2016/04/20		414	379		42	36		8	4		136	68
2016/04/21		617	757		63	50		12	8		202	164
2016/04/22		564	707		58	47		11	6		185	127
2016/04/23		377	453		38	38		7	5		123	62
2016/04/24		410	500		42	40		8	6		134	89

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2016/04/25	493	342	463	45,2	35	41	5,8	6	6	72	112	65
2016/04/26		405	491		41	39		8	5		133	66
2016/04/27		298	196		30	26		6	3		98	89
2016/04/28		467	574		48	40		9	6		153	123
2016/04/29		544	662		56	42		10	6		178	150
2016/04/30		734	910		75	56		14	9		240	120
2016/05/01		537	676		55	40		10	6		176	109
2016/05/02	522	307	446	44,3	31	42	5,5	6	5	56	100	52
2016/05/03		481	584		49	46		9	7		157	86
2016/05/04		470	383		48	31		9	6		154	77
2016/05/05		416	589		43	46		8	6		136	68
2016/05/06		625	715		64	69		12	13		205	161
2016/05/07		462	537		47	39		9	6		151	135
2016/05/08		466	571		48	43		9	7		152	94
2016/05/09	487	430	438	30,1	44	36	5,3	8	5	40	141	68

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2016/05/10		400	613		41	45		8	5		131	65
2016/05/11		380	499		39	46		7	5		125	62
2016/05/12		536	579		55	41		10	7		175	178
2016/05/13		638	782		65	53		12	9		209	104
2016/05/14		1003	1272		102	67		19	10		328	192
2016/05/15		258	302		26	23		5	3		84	72
2016/05/16	278	276	211	18,4	28	23	2,4	5	3	22	90	44
2016/05/17		413	485		42	34		8	5		135	121
2016/05/18		500	549		51	38		9	5		164	131
2016/05/19		374	452		38	35		7	5		122	100
2016/05/20		511	593		52	43		10	6		167	150
2016/05/21		640	733		65	49		12	8		210	195
2016/05/22		558	672		57	45		11	7		183	153
2016/05/23	542	407	533	40,5	42	43	6,8	8	6	118	133	116
2016/05/24		425	518		43	39		8	5		139	70

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2016/05/25		410	590		42	48		8	7		134	67
2016/05/26		438	737		45	47		8	6		143	72
2016/05/27		435	531		44	40		8	5		142	71
2016/05/28		382	461		39	39		7	5		125	62
2016/05/29		389	479		40	40		7	4		127	89
2016/05/30	597	397	516	38,2	41	41	4,5	8	5	65	130	63
2016/05/31		428	632		44	48		8	6		140	70
2016/06/01		435	524		44	45		8	5		142	71
2016/06/02		416	477		43	38		8	5		136	68
2016/06/03		424	515		43	41		8	5		139	69
2016/06/04		516	631		53	49		10	6		169	93
2016/06/05		461	562		47	43		9	5		151	75
2016/06/06	393	373	432	44,5	38	42	6,4	7	5	110	122	66
2016/06/07		414	500		42	41		8	6		136	68
2016/06/08		411	496		42	41		8	5		135	67

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2016/06/09		419	498		43	42		8	6		137	112
2016/06/10		380	436		39	39		7	4		125	63
2016/06/11		433	522		44	46		8	5		142	71
2016/06/12		355	424		36	40		7	5		116	58
2016/06/13	420	390	410	36	40	39	3,5	7	4	76	128	75
2016/06/14		317	381		32	33		6	4		104	52
2016/06/15		419	508		43	40		8	5		137	69
2016/06/16		328	385		33	39		6	5		107	54
2016/06/17		633	1226		65	72		12	8		207	104
2016/06/18		350	419		36	39		7	4		115	57
2016/06/19		401	469		41	45		8	8		131	66
2016/06/20	303	417	606	33,65	43	66	2,8	8	6	42	137	68
2016/06/21		598	733		61	53		11	7		196	98
2016/06/22		401	482		41	45		8	5		131	74
2016/06/23		406	487		41	43		8	5		133	66

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2016/06/24		426	521		44	38		8	5		140	71
2016/06/25		415	501		42	42		8	5		136	68
2016/06/26		387	465		39	41		7	5		127	63
2016/06/27	766	421	561	0	43	48	4,4	8	5	0	138	69
2016/06/28		462	454		47	35		9	5		151	76
2016/06/29		570	698		58	51		11	6		187	93
2016/06/30		343	410		35	39		6	5		112	70
2016/07/01		460	526		47	34		9	4		150	144
2016/07/02		509	626		52	49		10	6		167	101
2016/07/03		429	519		44	42		8	5		140	70
2016/07/04	508	260	395	40,3	27	38	4,5	5	5	103	85	105
2016/07/05		420	651		43	48		8	6		137	69
2016/07/06		401	499		41	51		8	6		131	66
2016/07/07		415	499		42	42		8	6		136	68
2016/07/08		538	654		55	52		10	7		176	92

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2016/07/09		466	564		48	46	0	9	6		152	77
2016/07/10		411	496		42	43		8	6		135	80
2016/07/11	534	367	456	40,9	37	43	5	7	5	27	120	54
2016/07/12		384	460		39	40		7	5		126	63
2016/07/13		610	760		62	50		12	7		200	160
2016/07/14		432	472		44	34		8	4		141	71
2016/07/15		435	646		44	48		8	6		142	71
2016/07/16		367	441		37	38		7	5		120	60
2016/07/17		311	364		32	38		6	5		102	51
2016/07/18	514	882	779	33,7	90	57	3,5	17	7	29	289	140
2016/07/19		548	671		56	48		10	7		179	90
2016/07/20		571	561		58	47		11	6		187	94
2016/07/21		416	585		42	47		8	6		136	68
2016/07/22		259	249		26	33		5	5		85	74
2016/07/23		419	501		43	44		8	6		137	69

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2016/07/24		401	477		41	44		8	6		131	66
2016/07/25		562	959		57	62		11	8		184	92
2016/07/26		427	609		44	46		8	6		140	70
2016/07/27		594	1117		61	62		11	8		194	97
2016/07/28		335	497		34	42		6	5		110	49
2016/07/29		632	783		65	53		12	6		207	104
2016/07/30		594	1002		61	64		11	7		194	97
2016/07/31		459	553		47	45		9	7		150	75
2016/08/01	557	480	728	43,85	49	51	3,2	9	6	79	157	74
2016/08/02		448	635		46	45		8	6		147	73
2016/08/03		479	581		49	45		9	6		157	78
2016/08/04		735	1321		75	75		14	10		241	120
2016/08/05		454	583		46	45		9	6		149	74
2016/08/06		389	528		40	47		7	6		127	64
2016/08/07		404	482		41	44		8	5		132	66

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2016/08/08		367	429		37	43		7	6		120	60
2016/08/09		486	580		50	46		9	7		159	128
2016/08/10		482	568		49	54		9	8		158	79
2016/08/11		460	527		47	37		9	6		150	118
2016/08/12		476	571		49	49		9	7		156	78
2016/08/13		418	499		43	44		8	6		137	68
2016/08/14		409	484		42	46		8	7		134	67
2016/08/15	569	370	500	63,5	38	45	4,7	7	6	46	121	59
2016/08/16		430	517		44	43		8	6		141	70
2016/08/17		575	682		59	49		11	6		188	94
2016/08/18		569	697		58	47		11	8		186	93
2016/08/19		515	623		53	51		10	6		169	84
2016/08/20		447	537		46	44		8	7		146	73
2016/08/21		414	495		42	42		8	7		136	68
2016/08/22	564	448	758	39,1	46	43	5,2	8	5	31	147	62

	COD (mgCOD/l)			TKN (mgTKN/l)			TP (mgTP/l)			TSS (mgTSS/l)		
Time (days)	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted	Measured	Estimated	Fitted
2016/08/23		451	546		46	44		9	6		148	74
2016/08/24		466	562		48	47		9	6		153	76
2016/08/25		450	497		46	45		9	5		147	74
2016/08/26		700	1129		72	66		13	9		229	115
2016/08/27		487	685		50	53		9	7		160	80
2016/08/28		936	1380		96	70		18	9		306	153
2016/08/29	1000	423	579	0	43	44	4,5	8	6	83	139	67
2016/08/30		477	573		49	48		9	7		156	78
2016/08/31		405	448		41	42		8	6		133	66

Appendix D: Input Parameters

The tables in this section summarises the inputs parameters that were used in the developed tool (PPET) in order to meet the objectives of this research project.

Table B - 1: General input parameters for plants A, B and C

Parameter	Abbreviation	Units	Range	Plant A	Plant B	Plant C
Design Sludge Age, SRT	SRT	d	15 to 25	10	10	10
factor of safety	Sf	-	1.1 to 1.5	1.25	1.25	1.25
Number of Anaerobic Reactors in Series	Nana	-	-	2	2	2
Population	Popn	-	-	5000	5000	5000
Energy cost		c/kWh	-	62.03	62.03	62.03
System Temperature	Design Temp	°C	15 to 25	18	18	18
Aeration power	P_O2	kgO^2/kWh	-	1.2	1.2	1.2
Diluted Sludge Volume Index	DSVI	mL/g	150 to 250	160	160	80
Peak factor (PWWF/ADWF)	fq	-	2 to 4	2	2	2

Table B - 2: Biological sizing parameters

Parameter	Abbreviation	Units	Range	Plant A	plant B	Plant C
Anoxic Vol.	V_ax	m^3	-	2376	2376	1157
Anaerobic Vol.	V_an	m^3	-	1010	1010	405
Total Aerobic	V_aer	m^3	-	2554	2554	4225
Aerobic fract.	f_Xaer	-	0 to 1	0.430	0.430	0.730
Anoxic fract.	f_Xd	-	0 to 1	0.400	0.400	0.200
Anaerobic fract.	f_Xana	-	0 to 1	0.170	0.170	0.070
SST Area	AST	m^2	-	1414	1414	1321

Parameter	Abbreviation	Units	Range	Plant A	plant B	Plant C
anoxic to anaerobic recycle ratio	r_recy	:1 w.r.t influent flow	0.5 to 5	1.00	1.00	1.00
mixed liquor recylce ratio	a_recy	:1 w.r.t influent flow	1 to 10	4.00	4.00	4.00
Sludge underflow recylce ratio	S_recy	:1 w.r.t influent flow	1 to 11	1.00	1.00	1.00
Fraction of influent flowrate (Qi) to Module 1	f_Qi_Mod 1	-	0 to 1	0.235	0.400	1.00

Table B - 3: Anaerobic digester inputs

Parameter	Abbreviation	Unit	Range	Plant A	plant B	Plant C
Fraction of primary sludge fed to AD	f_QPS_AD	-	0 or 1	1.00	1.00	1.00
Fraction of secondary waste fed to AD	f_QW_AD	-	0 or 1	1.00	1.00	1.00
Thickening effect on Primary Sludge (PS)	f_PS	%	0 to 100	1.00	1.00	1.00
Required Sludge Age for Anaerobic Digestion (AD)	Rs_AD_min	days	-	40.0	40.0	40.0
Selected Total Suspended Solids (TSS) Concentration	AD_TSS	mg/l	-	50000	50000	50000
pH	-	-	See [3]	8.00	8.00	8.00
Alkalinity	-	mg $CaCO_3$/l	See [4]	500	500	500
Volatile fatty acids	VFA	mg/l	See [5]	0.00	0.00	0.00

[3] If treating only WAS in the AD,then use pH of 7 – 8. If treating only PS in the AD, then use pH of 6.
[4] If treating only WAS in the AD,then alkalinity of 300 mg$CaCO_3$/l. If treating only PS in the AD, then use alakalinity of 1000 mg$CaCO_3$/l.
[5] If treating only WAS in the AD,then use VFA of 0 mg/l. If treating only PS in the AD, then use VFA of 450 – 500 mg/l.

Table B - 4: Effluent quality criteria

Parameter	Abbreviation	unit	Default	Special limit
Chemical Oxygen Demand	COD	mgCOD/l	30	30
Free and Saline Ammonia	FSA	mgN/l	2	2
Ortho-Phosphate	OP	mgP/l	2.5	2.5
Nitrates	NO3	mgN/	1.5	1.5
Total Suspended Solids	TSS	mgTSS/l	10	10

Appendix E: Steady-State Model Inputs

The following results from the fractionator were used as inputs for the full-scale steady-state model.

Table C-1: Influent COD characteristics

		Plant A			**Plant B**			**Plant C**
Sewage Characteristic	**Units**	**Raw**	**Settled**	**PS**	**Raw**	**Settled**	**PS**	**Raw**
Flow	Ml/d	170	168	1.70	59	58.4	0.590	4.02
Total COD	mgCOD/l	729	437	29597	750	450	30450	468
Total Soluble COD (filtered COD)	mgCOD/l	292	292	292	147	147	147	340
Total Particulate COD	mgCOD/l	437	146	29306	603	303	30303	128
Unbiodegradable Soluble COD fraction	mgCOD/mgCOD	0.096	0.160	0.002	0.069	0.116	0.002	0.070
Unbiodegradable Particulate COD fraction	mgCOD/mgCOD	0.110	0.060	0.183	0.125	0.040	0.249	0.130
Unbiodegradable Soluble COD	mgCOD/l	70.0	70.0	70.00	52.0	52	52	32.76
Unbiodegradable Particulate COD	mgCOD/l	80.2	26.2	5421	93.75	18	7593	60.84
Biodegradable Particulate COD	mgCOD/l	357	120	23885	509	285	22710	67.3
Biodegradable Soluble COD	mgCOD/l	222	222	222	95.0	95	95	307
Fermentable Biodegradable Soluble COD	mgCOD/l	193	193	193	95.0	95	95	257

		Plant A			Plant B			Plant C
Sewage Characteristic	**Units**	**Raw**	**Settled**	**PS**	**Raw**	**Settled**	**PS**	**Raw**
VFA fraction of COD	mgCOD/mgCOD	0.039	0.065	0.001	0.000	0.000	0.000	0.107
COD in Volatile Faty Acids	mgCOD/l	28.5	28.5	28.45	0.000	0.000	0.000	50
Total Biodegradable COD	mgCOD/l	579	341	24107	604	380	22805	374
Readilly biodeg fraction of COD	mgCOD/mgCOD	0.304	0.507	0.007	0.127	0.211	0.003	0.656
Fraction of COD that is BPO	mgCOD/mgCOD	0.490	0.273	0.807	0.679	0.633	0.746	0.144
Total Unbodegradable COD	mgCOD/l	150	96.2	5491	146	70.0	7645	93.6

Table C-2: Influent C characteristics

		Plant A			Plant B			Plant C	
Sewage Characteristic	**Units**	**Raw**	**Settled**	**PS**	**Raw**	**Settled**	**PS**	**Raw**	**Settled**
Total C	mgC/l	240	146	9543	255	152	10426	158	158
Total Soluble C	mgC/l	98.6	98.6	98.6	48.7	48.7	48.7	115	115
TotalParticulate C	mgC/l	141	47.0	9445	206	103	10377	42.5	42.5
Unbiodegradable Solunble C	mgC/l	24.0	24.0	24.0	17.2	17.2	17.2	11.2	11.2
Unbiodegradable Particulate C	mgC/l	27.9	9.13	1886	32.8	6.30	2656	21.2	21.2
Biodegradable Particulate C	mgC/l	113	37.8	7559	173	96.9	7721	21.3	21.3

		Plant A			Plant B			Plant C	
Sewage Characteristic	**Units**	**Raw**	**Settled**	**PS**	**Raw**	**Settled**	**PS**	**Raw**	**Settled**
Biodegradable Soluble C	mgC/l	74.6	74.6	74.6	31.4	31.4	31.4	104	104
Fermentable Biodegradable Soluble C	mgC/l	63.9	63.9	63.9	31.4	31.4	31.4	85.1	85.1
C in Volatile Faty Acids	mgC/l	10.7	10.7	10.7	0.000	0.000	0.000	18.7	18.7

Table C-3: Influent TKN characteristics

		Plant A			Plant B			Plant C
Sewage Characteristic	**Units**	**Raw**	**Settled**	**PS**	**Raw**	**Settled**	**PS**	**Raw**
Total Kjeldahl Nitrogen (N)	mgN/l	49.0	46.1	337.7	59.0	51.1	847	52.5
Total Soluble N	mgN/l	41.7	41.7	41.7	46.2	46.2	46.2	47.9
Total particulate N (Organic)	mgN/l	7.29	4.37	296	12.8	4.83	800	4.56
Unbiodegradable Solunble Organic N	mgN/l	4.29	4.29	4.29	1.79	1.79	1.79	1.61
Unbiodegradable Particulate Organic N	mgN/l	5.42	1.77	366	6.33	1.22	513	2.88
Biodegradable Particulate Organic N	mgN/l	1.87	2.60	-70.3	6.45	3.61	288	1.68
Biodegradable Soluble Organic N	mgN/l	3.12	3.12	3.12	1.14	1.14	1.14	4.32
Free and Saline Ammonia	mgN/l	34.3	34.3	34.3	43.3	43.3	43.3	42.0
Influent Nitrate/Nitrite (NO3-N/NO2-N)	mgN/L	0.000	0.000	0.000	0.000	0.000	0.000	0.000

		Plant A			Plant B			Plant C
Sewage Characteristic	**Units**	**Raw**	**Settled**	**PS**	**Raw**	**Settled**	**PS**	**Raw**
Fraction of influent TKN that is FSA	mgN/mgN	0.700	0.744	0.102	0.734	0.848	0.051	0.800
TKN fraction bound in USO	mgN/mgN	0.088	0.093	0.013	0.030	0.035	0.002	0.031
TKN fraction bound in UPO	mgN/mgN	0.111	0.038	1.085	0.107	0.024	0.606	0.055
TKN fraction bound in BPO	mgN/mgN	0.038	0.056	-0.208	0.109	0.071	0.340	0.032

Table C-4: Influent TP characteristics

		Plant A			Plant B			Plant C
Sewage Characteristic	**Units**	**Raw**	**Settled**	**PS**	**Raw**	**Settled**	**PS**	**Raw**
Total Phosphorus (P)	mgP/l	6.10	5.88	264	13.9	11.1	280	10.7
Total Soluble P	mgP/l	5.55	5.55	5.55	8.87	8.87	8.87	5.51
Total particulate P (Organic)	mgP/l	0.551	0.331	259	4.98	2.20	271	5.19
Unbiodegradable Solunble Organic P	mgP/l	1.23	1.23	1.23	0.004	0.004	0.004	0.231
Unbiodegradable Particulate Organic P	mgP/l	1.63	0.53	110	1.58	0.304	128	1.03
Biodegradable Particulate Organic P	mgP/l	2.31	0.77	154	3.395	1.9	151	0.024
Biodegradable Soluble Organic P	mgP/l	1.41	1.41	1.41	0.669	0.669	0.669	1.08
Ortho Phosphate	mgP/l	2.90	2.90	2.90	8.20	8.20	8.20	4.20
TP fraction that is OP	mgP/mgP	0.475	0.493	0.011	0.592	0.740	0.029	0.393
TP fraction bound in UPO	mgP/mgP	0.266	0.090	0.416	0.114	0.027	0.458	0.096

		Plant A			Plant B			Plant C
Sewage Characteristic	**Units**	**Raw**	**Settled**	**PS**	**Raw**	**Settled**	**PS**	**Raw**
TP fraction bound in PO	mgP/mgP	0.090	0.056	0.979	0.359	0.199	0.968	0.485
TP fraction bound in BPO	mgP/mgP	0.378	0.131	0.584	0.245	0.172	0.542	0.002

Table C-5:

		Plant A			Plant B			Plant C
Sewage Characteristic	**Units**	**Raw**	**Settled**	**PS**	**Raw**	**Settled**	**PS**	**Raw**
Influent Magnesium Concentration	mg/l	10.00	10.00	10.00	10	10	10	10
Influent Potassium Concentration	mg/l	10.00	10.00	10.00	10	10	10	10
Influent Calcium Concentration	mg/l	5.00	5.00	5.00	5	5	5	5
Influent TSS	mg/l	195	75.5	12026	350	141	21000	234
Influent Inorganic Suspended Solids	mg/l	32.2	26.2	626	32.2	6.49	2572	58.6

Table C-6

		Plant A			**Plant B**			**Plant C**
Sewage Characteristic	**Units**	**Raw**	**Settled**	**PS**	**Raw**	**Settled**	**PS**	**Raw**
TKN/COD Ratio	mgN/mgCOD	0.067	0.105	0.011	0.079	0.113	0.028	0.112
TP/COD Ratio	mgP/mgCOD	0.008	0.013	0.009	0.018	0.025	0.009	0.023
ISS/COD Ratio	mgISS/mgCOD	0.044	0.060	0.021	0.043	0.014	0.084	0.125
VSS/TSS Ratio	mgVSS/mgTSS	0.165	0.346	0.052	0.092	0.046	0.122	0.250

Appendix F: Fractionator Evaluation

The tables provided in this appendix give a detailed comparison of the fractionator outcome compared to Ekama (2009) models for a plant with influent measurements summarised in Table D- 1 and Table D- 2.

Table D- 1: Influent raw wastewater, primary sludge and effluent measurements

Time	Flowrate	COD	TKN	TSS	TP	FSA	OrthoP	Temperature	PS flowrate	Effluent COD
Days/hours	m^3/d	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	°C	m^3/d	mg/l
6:00 AM	21600	443	36.37	249	7.290	24.70	5.010	16	192.9	22.17
8:00 AM	30300	449	49.13	272	6.741	37.30	4.430	16	270.5	22.43
10:00 AM	90000	844	80.14	487	14.62	57.90	10.28	16	803.5	42.22
12:00 PM	103200	1161	98.19	679	20.75	67.60	14.77	16	921.4	58.06
2:00 PM	87000	1309	109.6	761	23.06	75.10	16.32	16	776.8	65.45
4:00 PM	70200	1341	115.7	785	23.99	80.40	17.09	16	626.8	67.03
6:00 PM	61200	1478	105.9	862	26.50	67.00	18.89	16	546.4	73.89
8:00 PM	69600	1372	97.85	792	23.76	61.70	16.7	16	621.4	68.61
10:00 PM	63600	1267	88.58	722	21.81	55.20	15.29	16	567.8	63.34
12:00 AM	58200	1214	74.89	687	20.25	42.90	14	16	519.6	60.70
2:00 AM	40800	1108	69.39	626	19.19	40.20	13.49	16	364.3	55.42

Time	Flowrate	COD	TKN	TSS	TP	FSA	OrthoP	Temperature	PS flowrate	Effluent COD
Days/hours	m^3/d	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	°C	m^3/d	mg/l
4:00 AM	26400	739	52.17	413	12.79	32.70	8.990	16	235.7	36.95

Table D- 2: Influent settled wastewater measurements

Time	Flowrate	COD	TKN	TSS	TP	FSA	OrthoP
Days/hours	m^3/d	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
6:00 AM	21407	236.8	29.40	92.25	5.895	24.67	5.010
8:00 AM	30029	239.7	42.06	100.2	5.327	37.27	4.432
10:00 AM	89196	451.1	66.94	179.8	11.96	57.92	10.28
12:00 PM	102279	620.3	79.97	250.4	17.09	67.57	14.77
2:00 PM	86223	699.2	89.06	280.6	18.93	75.08	16.32
4:00 PM	69573	716.2	94.76	289.5	19.76	80.44	17.09
6:00 PM	60654	789.5	82.82	317.8	21.83	67.04	18.89
8:00 PM	68979	733.1	76.33	292.2	19.44	61.67	16.70
10:00 PM	63032	676.7	68.77	266.7	17.81	55.24	15.29
12:00 AM	57680	648.5	55.87	253.9	16.42	42.90	14.00
2:00 AM	40436	592.1	52.06	231.4	15.70	40.22	13.49

Time	Flowrate	COD	TKN	TSS	TP	FSA	OrthoP
Days/hours	**m^3/d**	**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/l**
4:00 AM	26164	394.7	40.61	152.7	10.47	32.71	8.993

Table D- 3: COD comparison for fractionator results with models of Ekama (2009)

Influent Characteristic Components			Raw		Settled		Primary Sludge	
Sewage Characteristic	**Abbreviation**	**Units**	**Fractionator**	**Ekama (2009)**	**Fractionator**	**Ekama (2009)**	**Fractionator**	**Ekama (2009)**
Flow	Qi	Ml/d	87.00	60.00	86.22	59.46	0.78	0.5358
Total COD	Sti	mgCOD/l	1262	1150	693.7	614.0	64389	60636
Total Soluble COD (filtered COD)	Stsi	mgCOD/l	265.2	293.0	265.2	293.0	265.2	293.0
Total Particulate COD	Stpi	mgCOD/l	997.2	857.0	428.5	321.0	64124	60343
Unbiodegradable Soluble COD	Susi	mgCOD/l	78.38	57.50	78.38	57.50	78.38	57.50
Unbiodegradable Particulate COD	Supi	mgCOD/l	185.6	149.5	44.29	19.65	15870	14561
Biodegradable Particulate COD	Sbpi	mgCOD/l	811.6	707.5	384.2	301.4	48254	45783
Biodegradable Soluble COD	Sbsi	mgCOD/l	186.8	235.5	186.8	235.5	186.8	235.5
Fermentable Biodegradable Soluble COD	Sbsfi	mgCOD/l	127.0	185.5	127.0	185.5	127.0	185.5
COD in Volatile Fatty Acids	Sbsai	mgCOD/l	59.81	50.00	59.81	50.00	59.81	50.00
Total Biodegradable COD	Sbi	mgCOD/l	998.5	943.0	571.1	536.8	48441	46018

Influent Characteristic Components			Raw		Settled		Primary Sludge	
Sewage Characteristic	**Abbreviation**	**Units**	**Fractionator**	**Ekama (2009)**	**Fractionator**	**Ekama (2009)**	**Fractionator**	**Ekama (2009)**
Total Unbiodegradable COD	Sui	mgCOD/l	264.0	207.0	122.7	77.15	15948	14618

Table D- 4: Total carbon comparison for fractionator results with models of Ekama (2009)

Influent Characteristic Components			Raw		Settled		Primary Sludge	
Sewage Characteristic	**Abbreviation**	**Units**	**Fractionator**	**Ekama (2009)**	**Fractionator**	**Ekama (2009)**	**Fractionator**	**Ekama (2009)**
Total C	Cti	mgC/l	421.4	383.1	232.1	205.0	21441	20149
Total Soluble C	Ctsi	mgC/l	90.80	99.50	90.80	99.50	90.80	99.50
Total Particulate C	Ctpi	mgC/l	330.6	283.6	141.3	105.5	21350	20050
Unbiodegradable Soluble C	Cusi	mgC/l	26.17	19.18	26.17	19.18	26.17	19.18
Unbiodegradable Particulate C	Cupi	mgC/l	64.97	52.29	15.51	6.872156651	5556	5093
Biodegradable Particulate C	Cbpi	mgC/l	265.6	231.3	125.8	98.63	15794	14957
Biodegradable Soluble C	Cbsi	mgC/l	64.63	80.32	64.63	80.32	64.63	80.32
Fermentable Biodegradable Soluble C	Cbsfi	mgC/l	42.17	61.57	42.17	61.57	42.17	61.57
C in Volatile Fatty Acids	Cbsai	mgC/l	22.45	18.75	22.45	18.75	22.45	18.75

Table D- 5: TKN comparison for fractionator results with models of Ekama (2009)

Influent Characteristic Components			**Raw**		**Settled**		**Primary Sludge**	
Sewage Characteristic	**Abbreviation**	**Units**	**Fractionator**	**Ekama (2009)**	**Fractionator**	**Ekama (2009)**	**Fractionator**	**Ekama (2009)**
Total Kjeldahl Nitrogen (N)	Nti	mgN/l	111.4	89.90	92.04	71.90	2262	2088
Total Soluble N	Ntsi	mgN/l	80.21	63.60	80.21	63.60	80.21	63.60
Total particulate N (Organic)	Ntpi	mgN/l	31.20	26.30	11.83	8.30	2182	2024
Unbiodegradable Soluble Organic N	Nousi	mgN/l	1.355	1.000	1.355	1.000	1.355	1.000
Unbiodegradable Particulate Organic N	Noupi	mgN/l	12.54	10.09	2.992	1.327	1072	983.1698
Biodegradable Particulate Organic N	Nobpi	mgN/l	18.66	16.21	8.84	6.973	1110	1041
Biodegradable Soluble Organic N	Nobsi	mgN/l	2.068	3.000	2.068	3.000	2.068	3.000
Free and Saline Ammonia	Nai	mgN/l	76.79	59.60	76.79	59.60	76.79	59.60
Influent Nitrate/Nitrite (NO3-N/NO2-N)	NOxi	mgN/L	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Fraction of influent TKN that is FSA	fna	mgN/mgN	0.6892	0.6630	0.8343	0.8289	0.0339	0.0285
TKN fraction bound in USO	fnous	mgN/mgN	0.0122	0.0111	0.0147	0.0139	0.0006	0.0005
TKN fraction bound in UPO	fupn	mgN/mgN	0.1125	0.1123	0.0325	0.0185	0.4740	0.4710
TKN fraction bound in BPO	fnox	mgN/mgN	0.1675	0.1803	0.0960	0.0970	0.4905	0.4986

Table D- 6: TP comparison for fractionator results with models of Ekama (2009)

Influent Characteristic Components			Raw		Settled		Primary Sludge	
Sewage Characteristic	**Abbreviation**	**Units**	**Fractionator**	**Ekama (2009)**	**Fractionator**	**Ekama (2009)**	**Fractionator**	**Ekama (2009)**
Total Phosphorus (P)	Pti	mgP/l	23.63	20.07	19.74	16.44	456.3	422.9
Total Soluble P	Ptsi	mgP/l	17.63	15.04	17.63	15.04	17.63	15.04
Total particulate P (Organic)	Ptpi	mgP/l	6.006	5.030	2.108	1.400	438.6	407.9
Unbiodegradable Solunble Organic P	Pousi	mgP/l	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Unbiodegradable Particulate Organic P	Poupi	mgP/l	3.130	2.524	0.747	0.3317	267.7	245.8
Biodegradable Particulate Organic P	Pobpi	mgP/l	2.875	2.506	1.361	1.068	171.0	162.1
Biodegradable Soluble Organic P	Pobsi	mgP/l	2.235	0.89	2.23	0.89	2.235	0.89
Ortho Phosphate	Pai	mgP/l	15.39	14.15	15.39	14.15	15.39	14.15
TP fraction that is OP	fSPO4	mgP/mgP	0.6513	0.7050	0.7800	0.8607	0.0337	0.0335
TP fraction bound in UPO	fupP	mgP/mgP	0.1324	0.1257	0.0378	0.0202	0.5867	0.5812
TP fraction bound in PO	fSPI	mgP/mgP	0.2541	0.2506	0.1068	0.0852	0.9614	0.9644
TP fraction bound in BPO	fXPB	mgP/mgP	0.1217	0.1249	0.0690	0.0650	0.3747	0.3833

Table D- 7: Influent solids comparison for fractionator results with models of Ekama (2009)

Influent Characteristic Components			Raw		Settled		Primary Sludge	
Sewage Characteristic	**Abbreviation**	**Units**	**Fractionator**	**Ekama (2009)**	**Fractionator**	**Ekama (2009)**	**Fractionator**	**Ekama (2009)**
Influent TSS	XO	mg/l	783.3	665.0	282.5	245.0	56378	47277
Influent Inorganic Suspended Solids	Xioi	mg/l	124.4	99.80	0.00	34.3	13931	7369
TKN/COD Ratio	Nti/Sti	mgN/mgCOD	0.088	0.078	0.133	0.117	0.035	0.034
TP/COD Ratio	Pti/Sti	mgP/mgCOD	0.0187	0.0175	0.0284	0.0268	0.0071	0.0070
ISS/COD Ratio	Xiss/Sti	mgISS/mgCOD	0.0985	0.0868	0.0000	0.0559	0.2164	0.1215
VSS/TSS Ratio	XV/XO	mgVSS/mgTSS	0.8412	0.85	1.00	0.8600	0.7529	0.8441

Appendix G: User Manual

A.1 Introduction

This user manual is one of three deliverables that were to be submitted at the end of a study on the impact return dewatering liquor on the overall plant performance in the South African context; the other deliverables being a Plant Performance Evaluation Tool (PPET) and a Detailed Report. PPET was developed with the aim of converting complex plant-wide steady-state models into simple evaluation tools with the intent of evaluating the plant performance (i.e. effluent quality and cost).

The main objectives of PPET are:

- Evaluate the impact of return dewatering liquor on the overall plant performance (cost and effluent);
- Provide a recommendation for a suitable SSTP for best effluent quality and lowered operational costs; and
- To educate the user about treatment processes and how different decisions affect the overall plant performance.

Due to the complex processes running in the background, PPET requires a strong computer with a fast CPU for it to function.

A.2 User Interface

A.2.1 Home

Upon opening PPET, the home page is displayed. A brief introduction to the tool is provided.

➢ Please click on the Start button to proceed with this tool.

➢ By Clicking on the Start button, you will be taken to the Input Parameters tab.

A.2.1.1Input Parameters

This page requires entering all raw and settled wastewater (WW) inputs. It has been colour-coded such that the user can easily follow the instructions given. Where input parameters are not known, it is recommended that a value within the given range should be chosen.

➢ A reset button has been provided for clearing all inputs if needed.

Step 1: General Input

➢ Please enter the "blue" values (either for raw or settled wastewater) for the different parameters as shown in Table A-2. If the input value of a parameter is not known, please select a value within the given range of the parameter.

Table A-2: General input parameters

General Input					
Parameter	**Abbreviation**	**Value @ 20 °C**		**Range**	**Unit**
		Raw WW	**Settled WW**		
Design Sludge Age, SRT	SRT	10	10	15 to 25	d
factor of safety	Sf	1.25	1.25	1.1 to 1.5	Constant
Number of Anaerobic Reactors in Series	N_{ana}	2	2	-	-
Population	Popn	5000	5000	-	-
Energy cost		62.03	62.03	-	c/kWh
System Temperature	Design Temp	18	18	15 to 25	°C
Aeration power	P_O2	1.2	1.2	-	kgO_2/kWh
Diluted Sludge Volume Index	DSVI	160	160	150 to 250	mL/g
peak factor (PWWF/ADWF)	fq	2.0	2.0	2 to 4	-

Note:

- Sludge retention time (SRT) is the length of time (in days) that sludge remains in the reactor, it is given by Equation A- 1:

$$\text{SRT} = \frac{\text{Total reactor volume}}{\text{Waste flowrate}} \qquad \text{Equation A- 1}$$

- There are different tests that are used to measure sludge settleability.
    - The traditional test for measuring sludge settleability is **Sludge Settleability Test (SVI)**, however, it does not provide the best measurement due to variation in the test results with respect to sludge concentration and stirring effects, the dependency of the test on the cylinder diameter and depth, etc.
    - **Diluted Sludge Volume Index (DSVI)**, is an improved test for measuring sludge settleability. It is the volume (ml) occupied by 1 g of sludge after 30 minutes settling in a one-litre measuring cylinder. DSVI falls within the 150 to 250 ml/l range.

Step 2: Biological Reactor Sizing

This step focuses more on the actual sizing/fractionation of the flows and mass fractions in the reactor.

➢ Please enter the blue parameters as shown in Table A-3.

Table A-3: Biological reactor sizing parameters

Biological Reactor Sizing Parameters					
Parameter	**Abbreviation**	**Input**		**Range**	**Unit**
		Raw WW	**Settled WW**		
Total Vol. (VAS)	V_AS	5940	5940	-	m^3
Aerobic Reactor Concentration	Xt	4800	4800	-	mgTSS/l
Aerobic fract.	f_Xaer	0.43	0.43	0 to 1	-
Anoxic fract.	f_Xd	0.4	0.4	0 to 1	-
Anaerobic fract.	f_Xana	0.17	0.17	0 to 1	-
SST Area	AST	1414	1414	-	m^2
anoxic to anaerobic recycle ratio	r_recy	1.00	1.00	0.5 to 5	:1 w.r.t influent flow
mixed liquor recylce ratio	a_recy	4.00	4.00	1 to 10	:1 w.r.t influent flow
Sludge underflow recylce ratio	S_recy	1.00	1.00	1 to 11	:1 w.r.t influent flow
Fraction of influent flowrate (Qi) to Module 1	f_Qi_Mod 1	0.4	0.4	0 to 1	-

- The anaerobic (f_xana), anoxic (f_xd) and aerobic mass fractions (f_xaer) can be calculated using the formulae below:

  - For MLE and 3-Stage Phoredox systems:

$$\mathrm{f_{xana}} = \frac{\mathrm{V}_{anaerobic}}{\text{Total volume}} \quad \text{Equation A- 2}$$

$$\mathrm{f_{xd}} = \frac{\mathrm{V}_{anoxic}}{\text{Total volume}} \quad \text{Equation A- 3}$$

$$\mathrm{f_{xaer}} = \frac{\mathrm{V}_{aerobic}}{\text{Total volume}} \quad \text{Equation A- 4}$$

  - For the UCT system:

$$\mathrm{f_{xana}} = \frac{\mathrm{V}_{anaerobic} \times X_T \times \frac{r}{1+r}}{MX_T} \quad \text{Equation A- 5}$$

$$\mathrm{f_{xd}} = \frac{\mathrm{V}_{anoxic} \times X_T}{MX_T} \quad \text{Equation A- 6}$$

$$\mathrm{f_{xaer}} = \frac{\mathrm{V}_{aerobic} \times X_T}{MX_T} \quad \text{Equation A- 7}$$

  - For the JHB system:

$$f_{xana} = \frac{V_{anaerobic} \times X_T \times \frac{s}{1+s}}{MX_T}$$ Equation A- 8

$$f_{xd} = \frac{V_{anoxic} \times X_T}{MX_T}$$ Equation A- 9

$$f_{xaer} = \frac{V_{aerobic} \times X_T}{MX_T}$$ Equation A- 10

Where:

- MXT Total load of wasted activated sludge (kgTSS)
- XT Concentration of waste activated sludge (kgTSS/m^3)
- $V_{anaerobic}$ Volume of anaerobic reactor (m^3)
- V_{anoxic} Volume of anoxic reactor (m^3)
- $V_{aerobic}$ Volume of the aerobic reactor (m^3)

The sum of the different mass fractions should equal to 1.

a-prac stands for practical recycle ratio from the aerobic reactor to the anoxic reactor. It is recommended that this value should not exceed 6 since, for a > 6, the overall benefits in comparison to costs are not worth it. The other recycle ratios (i.e. the r and s) have been assumed to be equal to 1.

Step 3: Anaerobic Digestion (AD)

The PS and WAS are treated in the AD to reduce the fraction of active biodegradable organics in them before disposal.

➢ Please enter the blue parameters as shown in Table A-4.

Table A-4: Anaerobic digestion input parameters

Anaerobic Digestion (AD)					
Parameter	Abbreviation	Input		Range	Unit
		Raw WW	Settled WW		
Fraction of primary sludge fed to AD	f_QPS_AD	1	1	0 or 1	-
Fraction of secondary waste fed to AD	f_QW_AD	1	1	0 or 1	-
Thickening effect on Primary Sludge (PS)	f_PS	100%	100%	0 to 100	%
Required Sludge Age for Anaerobic Digestion (AD)	Rs_AD_min	60	60	-	Days
Selected Total Suspended Solids (TSS) Concentration	AD_TSS	50000	50000	-	mg/l
pH		8.0	8.0	See Step 3	-
Alkalinity		500	500	See Step 3	mg $CaCO_3$/l
Volatile fatty acids	VFA	0.00	0.00	See Step 3	mg/l

Note:

- It is recommended that the pH, alkalinity and VFA concentration of WAS and PS sludge should be measured. Figure A-1 shows typical values for treating WAS or PS separately.

If treating only WAS in AD	If treating only PS in AD
pH = 7 to 8 Alkalinity = 300 mgCaCO3/l VFA = 0 mg/l	pH = 6 Alkalinity = 1000 mgCaCO3/l VFA = 450 to 500 mg/l

Figure A-1: Typical values of pH, alkalinity and VFA concentration

Step 4: Effluent Quality Criteria

➢ Please enter the plant's effluent quality criteria as shown in Table A-5.

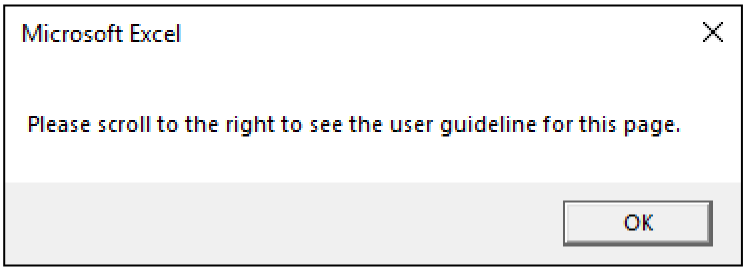
Table A-5: Effluent quality criteria inputs

Effluent Quality Criteria				
Parameter	Abbreviation	Special limit	Default	unit
Chemical Oxygen Demand	COD	30	30	mgCOD/l
Free and Saline Ammonia	FSA	2	2	mgN/l
Ortho-Phosphate	OP	2.5	2.5	mgP/l
Nitrates	NO_3	1.5	1.5	mgN/
Total Suspended Solids	TSS	10	10	mgTSS/l

Note:

- If no special permission has been granted with respect to having a different effluent criterion, use the defaults special limit values.

➢ Please click on the Data Reconciliation tab to go to the next step.



A.2.2 Data Reconciliation

This section requires adding influent measurements that have been made on a yearly, monthly basis or diurnally. The data provided is used to estimate the missing influent measurements through the interpolation and fitting processes (see steps 2 and 3 below). Once this process is complete, the generated influent measurements are combined to characterise the wastewater.

<u>This tool is limited to not more than one-year plant data.</u>

Step 1

➢ Please click on the reset button to empty the data cell, then enter the available plant measurements.

Note:

- **<u>All measurements inputs should have a flow rate measurement.</u>**

- Flowrate and COD are the most important measurements. It is recommended that many successive blanks of COD measurements should be avoided as much as possible to avoid skewed results from the interpolation and fitting processes.
- It is recommended that a considerable amount of data should be entered for more accurate influent wastewater characterisation. The richer the influent data measurements, the more accurate the wastewater characterisation will be. The opposite is true.

➢ **<u>Please note that Excel will be frozen during the execution of steps 2 to 4.</u>**

Step 2

➢ Please click on the "INTERPOLATE" button.

Note:

- This process takes several minutes to complete.
- The interpolation process is for interpolating values to fill in the missing gaps in the measurements.

Step 3

➢ Please click on the "FIT" button.

Note:

- This process takes about 2 hours to complete.
- The fitting process is used for calculating the actual values where the interpolated COD and influent flowrate values were estimated.

<u>After the fitting process is complete, you will be taken to the plant configuration tab.</u>

A.2.3 Plant Configuration

This section consists of selecting the biological nutrient removal plant layout and the type of influent wastewater.

Step 1

- Please select between Raw or Settled Wastewater by click on either of the buttons. By selecting the Raw Wastewater, the button will be highlighted as shown below.

Step 2

- Please click on one of the buttons to select the biological nutrient removal layout of your choice.
- Four configurations have been given. Figure A-2 shows the selection of the JHB layout.

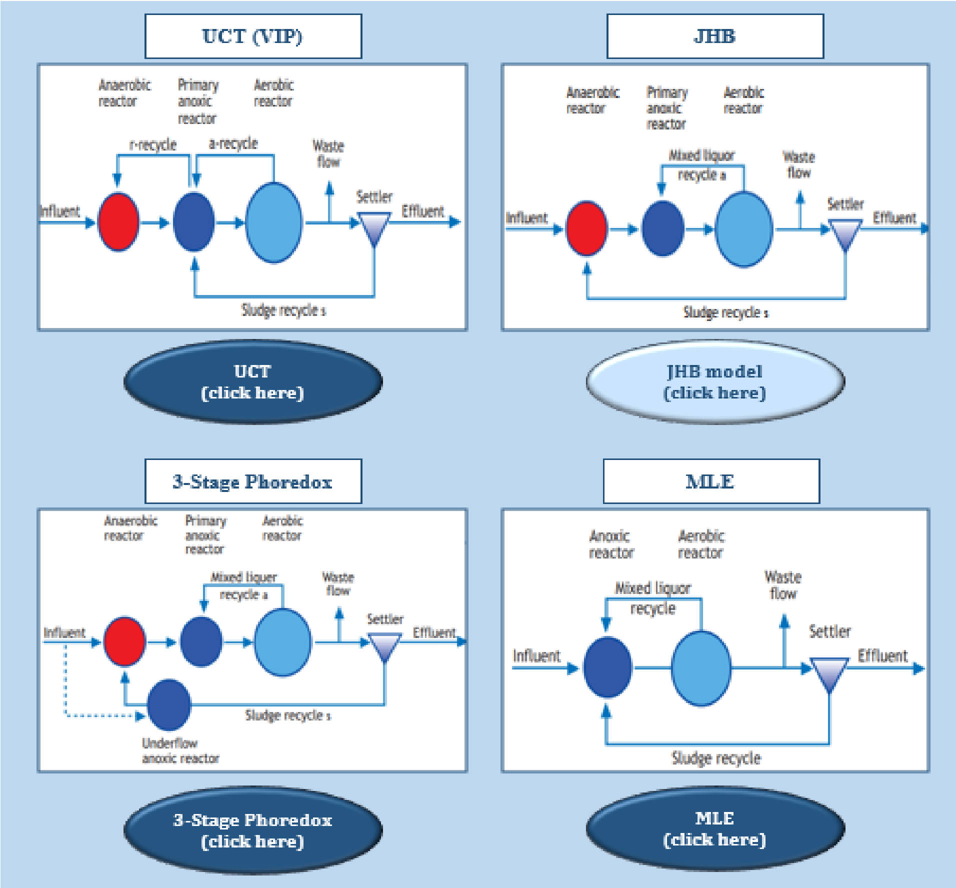


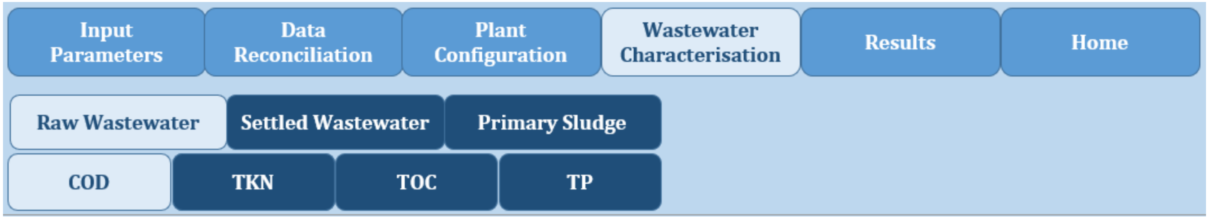
Figure A-2: Plant configuration

- By click on any of the buttons, in this case, the JHB layout, the model will take several minutes to run after which you will be taken to the Wastewater Characterisation tab.

A.2.4 Wastewater Characterisation

The main aim of this page is for educational purposes. The provided characterisations are used as inputs for the biological nutrient removal models.

- Detailed wastewater characterisation (COD, TKN, TOC and TP) is provided under this tab.



The buttons have been colour-coded to make this page easier to navigate. Click on the different button combinations to look at different results. For example, to view the raw wastewater characterisation of TKN, Click on the Raw Wastewater button, then the TKN button.

- The raw and TKN buttons will be highlighted as shown in Figure A-3.

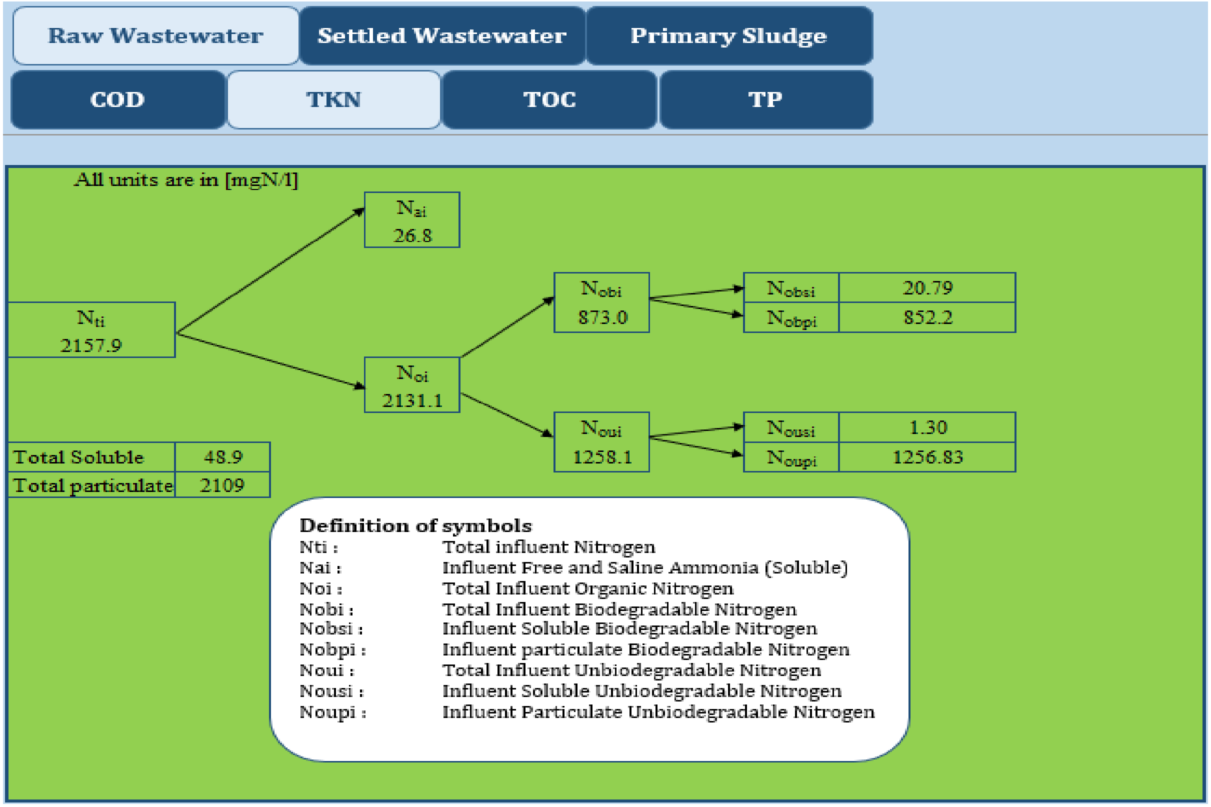


Figure A-3: Raw wastewater TKN characterisation

A.2.5 Results

Data from a South African plant has been used for this demonstration. Several results, based on the inputs, for different biological reactor layouts (i.e. UCT, JHB, MLE and 3-Stage Phoredox) have been summarised.

- Figure A-4 shows a picture from the interface of the results section once the JHB model has completed running. To view, any of the results click on the buttons.

Figure A-4: Interface for the results section

- Please choose which results to view by clicking on the respective button. For example, by clicking on the Biological Reactor button the results will be displayed as shown in Table A-6, and the results will be displayed.

Table A-6: Biological reactor results

Biological Reactor | Dewatering Liquor | Effluent Quality | Plant Performance | Recommendation

Parameter	Units	No side-stream treatment	Struvite precipitation	BABE process
Minimum sludge age for nitrification	days	8.35	8.35	8.35
Optimum a- recycle ratio	ratio	10.00	10.00	10.00
Carbonaceous Oxygen demand	KgO/d	4244	4244	4244
Nitrification oxygen demand	KgO/d	651	608	486
Peak oxygen demand	KgO/d	4487	4471	4425
Aeration Power Requirements	kW	224	224	221
Secondary Sludge produced	kgTSS/d	2882	2820	2882
PolyP produced in WAS (excess P removal)		35	16	34.86

Note:

- **Effluent Quality**

- The effluent quality results highlighted in red (Table A-7) are those that exceed the effluent quality limit (Table A-5).

Table A-7: Effluent quality results

Biological Reactor | Dewatering Liquor | Effluent Quality | Plant Performance | Recommendation

Parameter	Units	No side-stream treatment	Struvite Precipitation	BABE Process
Effluent COD concentration	mgCOD/l	21.25	21.25	21.25
Effluent TKN conc (nitrification)	mgN/l	3.50	3.50	2.42
Effluent Ammonia	mgN/l	2.20	2.20	1.12
Effluent NO_3 conc (denitrification)	mgN/l	3.08	2.88	2.30
Effluent TP	mgP/l	0.37	0.37	0.37
PO4	mgP/l	0.00	0.00	0.00

- **Plant Performance**

- The plant performance was evaluated based on two indices, namely the Effluent Quality Index (EQI) and the Operational Cost Index (OCI).
- The impact of returning dewatering liquor at a different percentage on the EQI and OCI has been summarized in several graphs as shown in Figure A-5.

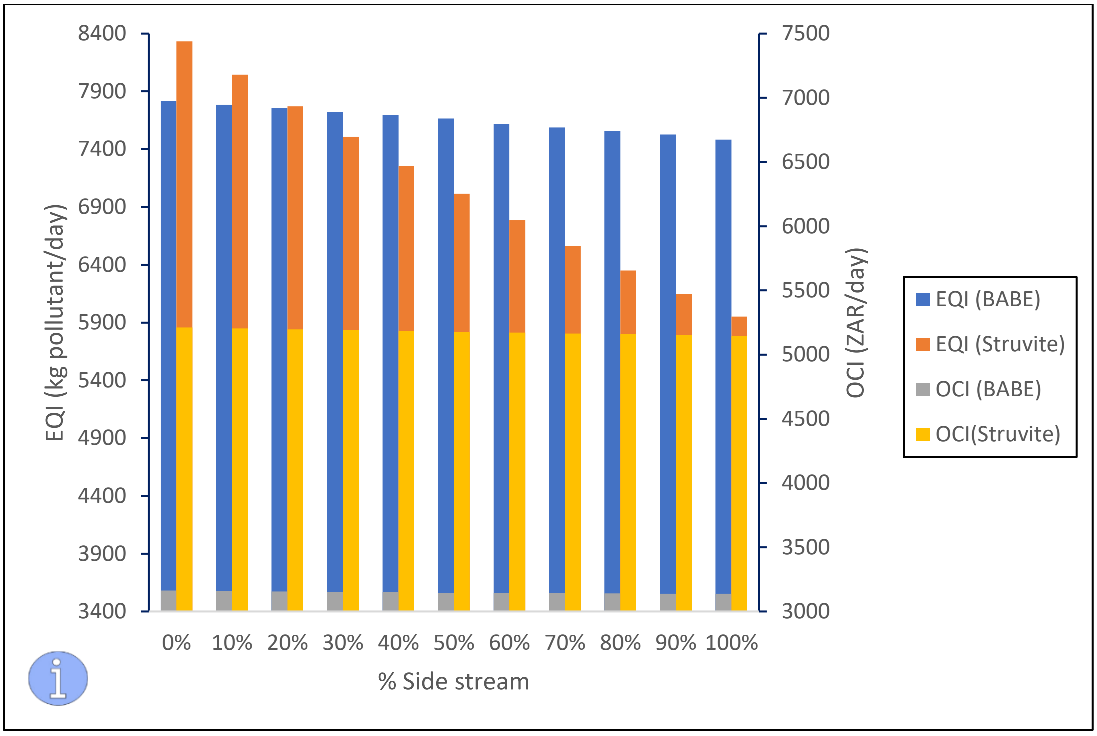


Figure A-5: Example of EQI and OCI variation with the percentage of DWL treated

- Please click on the info  button for more information about interpreting the graph. A text box will be displayed as shown in Figure A-6.

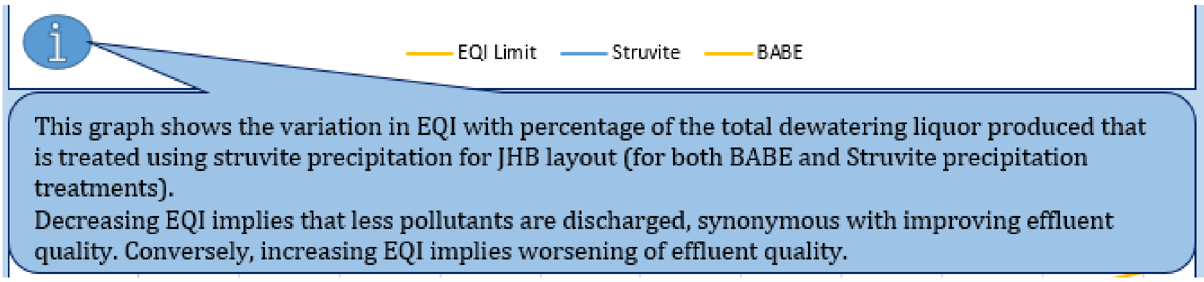


Figure A-6: Extra information in the text box